Sensitivity of Infrastructure Performance to Initial Design and Construction Standards

by

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Diplôme d'Ingénieur Généraliste
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(June 1997)

Submitted to the Department of Civil and Environmental Engineering in Partial Fulfillment of the Requirements for the Degree of

Master of Science

at the

Massachusetts Institute of Technology

September 1997

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Abstract

Infrastructure systems are usually associated with major capital investments. Because of the many benefits to users and society at large, infrastructure performance is of major importance and interest. Performance throughout the lifetime of a facility is in part influenced by factors that are decided upon during the period of initial provision. The objective of this thesis is, thus, to explore the sensitivity of infrastructure performance to changes in these initial provision variables.

Initial provision decisions, in addition to determining design and construction costs, affect deterioration rates and maintenance needs. Deterioration increases the maintenance required and, consequently, the corresponding cost the agency incurs operating the system. Furthermore, deterioration affects user costs and benefits by reducing the quality of service received by the users. There are, hence, two dimensions to the problem of interest. On the one hand, there is an aggregate perspective that considers the economic dimension and the relationships amongst the costs and benefits associated with the various decisions and activities. On the other hand, there is a more disaggregate perspective that explicitly considers the deterioration process itself.

After the presentation of the developed conceptual framework aimed at addressing the problem of assessing the sensitivity of infrastructure performance to initial provision variables, two approaches are explored via two case studies. First, an aggregate cost-based approach explores the sensitivity of maintenance expenditures to initial provision costs for Light Rail transit infrastructure. Second, a disaggregate deterioration-based approach where highway bridge deck scenarios are used in explicitly modeling performance outcomes as a function of initial provision variables is explored.

The cost- and deterioration-based approaches pursued in their respective case studies demonstrate the validity of the methodologies, even though the specific results with regards to Light Rail and Bridge Deck infrastructure are primarily illustrative in nature.

Finally, the applications of the methodologies to Cost Benefit Analysis and Contract Design and Monitoring are discussed, with specific examples related to Tren Urbano, a Heavy Rail transit system currently under construction in San Juan, Puerto Rico. Some extensions of the developed methodologies and further research directions are also discussed.

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Acknowledgments

Giving thanks is usually easier than being thanked. Nevertheless, I would like to express my deepest recognition to all the people who have contributed to this research and to making my stay at MIT an academically challenging, but pleasant one. My wish it is, that this recognition does not go unheard.

First and foremost, I would like to express my most sincere gratitude to Dr. Rabi Mishalani, without whom none of this would have happened. The teachings that were passed on to me will remain invaluable. As a mentor, advisor, teacher, and friend, I do not know anyone better. Thanks for making this experience, the wonderful experience that it has been.

My gratitude also goes out to Professor Nigel Wilson for guiding me with his immense knowledge on urban transportation and his witty British humor.

Thank you also to Ken Kruckemeyer, John Miller, Fred Salvucci, Antonio Gonzales, Edward Thomas, Carl Martland, Joe Ferretti, Antonio Cabrerra, and Curtis Chase for their experience and insights into transit related problems.

Thank you also to the Tren Urbano Program and research staff. The exchanges with the professors and students from the University of Puerto Rico and the Tren Urbano Office staff were very valuable. I shall not forget the funding diligently provided to me by this unique research program.

My personal thanks go out to "Le Cercle" for helping me retain my mental sanity throughout the year. I could not have made it through without your support. In particular, I would like to thank Arnaud M. for bearing with me through thick and thin, Eric D. for reminding me that life is a joyful ride, Stephan M. for his magic potion, and Sébastien F. for his wits and charms.

No words can express how much love I have for my mother. Thanks for pushing me just hard enough to reach as far as possible.

Finally, my Angel, Haziel, and all my friends here in the US and in France are assured of my eternal commitment. Life would be pretty dull without you. And to all whom I forgot to mention here, I express my thanks also. Rarely has one seen me ungrateful to those who deserve it.

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CHAPTER 1
INTRODUCTION

Infrastructure is the backbone of a country's economy and is necessary to sustain the level of activity generated by today's urban lifestyle. Infrastructure includes roads, highways, bridges, transit systems, interstate highways and railroads, sewer systems, phone and electricity lines. One of the key characteristics of infrastructure systems is that they are long-lived and, consequently, go through various stages ranging from planning, construction, service-provision to deterioration, and ultimately decay and replacement.

Usually, these infrastructure systems are associated with to massive capital investments. However, there is no conclusive knowledge on how the factors that are decided upon during the conception and construction phases impact the performance of the facility during its lifetime. Not many studies have been published about how, if at all, the decisions that generate all the initial capital cost influence the level of service that the system provides to the users, the maintenance costs that are required to sustain this level of service and the duration for which the performance remains acceptable.

Now that there is more data available due to advances in infrastructure management techniques, we are in a better position to assess the relationships that exist between initial decisions concerning design and construction and the performance of an infrastructure.

1.1 BACKGROUND

When examining infrastructure, the first remark to make is that the useful lifetime usually extends further than most of the objects that surround us. Periods of 30 to 50 years are often considered; sometimes, even more. Because we are dealing with such durations, the aging process is to be given a lot of attention, for it is the determinant of total lifetime and life cycle cost.

Among the factors that influence the deterioration process are the following:

- Design standard;
- Construction technique and quality;
- Maintenance and rehabilitation;
- Usage levels; and,
- Environment.

Designers have to choose among several concrete strengths for a bridge deck, for example. Construction related decisions are also important for they determine the tolerances to which the system is built and the types of material that are used. For example, track ballast quality is very much related to the quality of stones and rocks that are brought on site. Furthermore, the quality of the implementation of the design, the respect of the design specifications and resistance tests are crucial to ensure adequate strength to the structure. This extra-care not only affects the cost of providing the facility but also its resistibility to deterioration and to weathering. Maintenance and rehabilitation have to be scheduled and their intensity decided upon. This will determine how well further deterioration is avoided and how well existing defects are remedied against. Usage level also has a very obvious impact on the deterioration of a facility. The more a rail is traveled upon for example, the more load and crack-resulting stresses it has to sustain, and the more it wears out due to friction with the wheels. Finally, weathering also increases deterioration. Humidity and freeze-thaw cycles are all factors that have substantial influence on the deterioration rates.

All these factors influence the aging process thus the useful lifetime of the infrastructure. They, consequently, affect the Life Cycle Cost, through the condition of the infrastructure and the expenditures required to keep it operational.

Furthermore, infrastructure deterioration is in general non-linear. The process starts off slowly in the early years (once the "Infant Illness" period, which represents the period when early but small defects show up and get repaired, has been overcome). The deterioration rate increases as the facility ages. Maintenance and rehabilitation have to be scheduled so as to ensure acceptable performance to the user over the longest period possible but with the least possible total cost. The non-linearity typically manifests itself through the acceleration of the deterioration, as the facility gets into worse condition states. An example of this acceleration can be drawn from roads. As cracks appear at the surface, they allow water to seep through to the internal structure. This causes a reduction in the resistivity to loads, which translates into increases in cracks in the immediate proximity of the initial crack. As more and more water seeps through, these cracks increase in size resulting in potholes. This example illustrates how deterioration triggers further deterioration, actually accelerating the overall degradation process. This process is thus non-linear because the deterioration is not happening at a steady, unchanging pace. Much rather, it speeds up as the condition of the facility gets worse.

This strong non-linearity is the cause of a lot of deterioration problems in real life. Because once defects start to appear, the deterioration rate is already such that the maintenance required to effectively circumvent the problem is too high, and major rehabilitation and reconstruction is very often needed. It is also this non-linearity that makes it hard to assess the useful-lifetime of a facility. With proper care and preventive maintenance programs, the facility can perform well over an extended period of time. But if it is left to deteriorate, it will not provide the level of service that it is supposed to.

Therefore, one of the objectives of infrastructure management is to maintain adequate performance for the longest period possible. In order to do so, decision-makers need the ability to predict the condition of a facility based upon its condition, the maintenance policy adopted and the usage (among other influential variables) at the time maintenance decisions are made. But since another objective is to minimize expenditures while providing satisfactory service, the cost component is very important to consider. The extreme scenario of exceptional quality, "gold plating" a road for example, is not a sensible one for no agency disposes of that amount of money, even though the problem of maintenance would therewith be solved. This utopian example introduces the underlying problem that the infrastructure manager faces: the trade-off that needs to be assessed during the early phases of an infrastructure project. A balance has to be struck between initial quality and costs on one side, and performance and maintenance expenditures on the other. One extreme is a state-of-the-art system that deteriorates very fast due to very limited maintenance and poor quality. The other extreme is a lower-standard facility that yields acceptable performance over a longer period of time because it deteriorates slower. There are two consequences to this decision. The first one concerns the useful lifetime of the system, and how far out in time it provides an acceptable level of service. The time dimension will determine how well the initial costs are amortized. The second consequence is the split between user costs, incurred by the users of the system when it is not performing well, and "agency" costs, disbursed to operate the facility. User costs are for example increased travel time, discomfort, and vehicle repair cost due to bad road conditions. Agency costs are for instance maintenance-related expenditures. Both costs have to be considered jointly before taking any decisions.

New York City's subway comes out of a period of decaying infrastructure and several derailments. US Highways have been suffering from the reduction in spending by the government, in a period where it needs it the most (Nation's Business 1989). Similarly, the failure of bridge decks have resulted in fatalities and their condition is getting worse every year since more than 42% of the nation's bridges were structurally deficient in 1993 (Martinelli and Halabe, 1993). The interrogation therefore becomes: is this only a consequence of poor maintenance, or, on the contrary, inappropriate designs and insufficient construction quality leading to accelerated deterioration that cannot be coped with under normal operation of the system? The problem of infrastructure deterioration thus needs to be addressed and considerations about how to influence and predict the performance and increase the useful lifetime of a facility through sound initial decision-making would be beneficial.

1.2 OBJECTIVES

The main objective of this research is, therefore, to determine the extent to which infrastructure performance is sensitive to initial conditions.

This research is aimed at providing a better understanding of this sensitivity. The goal is to show which decisions matter in the earlier phases of a project. This can be achieved by determining the impact of changes in initial conditions on the long-term infrastructure condition state placing emphasis on the significance, magnitude and direction of this impact.

There are new infrastructure systems built every day. On some of these systems, a special effort is put into forecasting future expenses and trying to include this forecasted value in the early decision-making process. Tren Urbano, the urban heavy rail system that is being built in San Juan, Puerto Rico, is among these examples. The opportunities presented by Tren Urbano are twofold. First, because only the first stage (phase I) has been designed as of 1997, and at least two more are planned (phases IA and II), the time is just right to think about how to increase long-term performance through decisions that are to be taken during the planning stages of the forthcoming phases. Furthermore, because the first phase might already be in service at the time of those decisions, they could be based on data collected during the first years of service. Once maintenance effectiveness has been established and deterioration rates determined, much more informed decisions can be taken when planning the extensions. The second opportunity is generated by the contractual agreement governing the procurement and provision of Tren Urbano. This project is the first Design Build Operate public transit project receiving funds from the US's Federal Transit Administration. Having a single consortium of companies provide and agree upon design, construction and operation has many advantages. One of them is that, ideally, all these three components of infrastructure provision need to be coordinated, and the *cumulative* costs minimized. This favors long-term considerations about the project and requires accurate prediction of the condition and related expenses, in order to make the best decisions. However, this form of agreement could also have potential drawbacks due to the fact that the duration of the contract is limited to five years (with possible extension to ten). The fact that there are two strong actors in the decision-making process – the government of Puerto Rico, acting as the owner, and the private consortium, acting as a contractor – can bring conflicting interests into the picture. The government aims at the best long-term performance at the lowest price, whereas the consortium aims at maximum profit over the duration of the contract. One of our objectives is, therefore, to provide sufficient insight on how to best make common agreements in such cases, benefiting both parties through adequate prediction of the consequences of initial provision decisions on long-term condition, thus on costs and performance.

1.3 RESEARCH SCOPE AND APPROACH

In the light of the challenges that infrastructure deterioration poses, the question of interest to us is to determine the extent to which infrastructure performance is sensitive to initial design and construction standards. Behind this question lies the problem facing decision-makers that we mentioned previously: is it possible to influence the evolution of the condition of a facility through sound decisions made in the early stages of the project, based on a solid understanding of the impacts of these decisions?

Figure 1 presents in condensed form the infrastructure performance framework that we will develop more in detail in Chapter 2. The initial provision decisions influence the design and construction standards and, consequently, the cost related to the provision of the facility. These design and construction standards, in turn, influence the deterioration process. Deterioration is also influenced by uncontrollable temporal factors, namely environment and usage, and the maintenance policy resulting from the maintenance decisions. The maintenance decisions are affected by the condition resulting from the deterioration. Finally, the cost resulting from the maintenance decisions and the user costs associated with the effect of usage given the deterioration of the facility join the previously mentioned design and construction cost.

Hence, there are several levels of aggregations that can be thought of to approach the problem. It is worthwhile to explicitly examine a process to really understand its workings. However, it is also important to step back and observe the broader perspective. Figure 1 shows two possible levels of detail that can be pursued when considering infrastructure deterioration. From the most aggregate perspective, we can consider the two cost extremities of the framework. The advantages of this approach are the use of variables common to all parties involved and the insurance of not missing important relationships. This approach tries to predict how a change in the decision process influences user and agency costs.

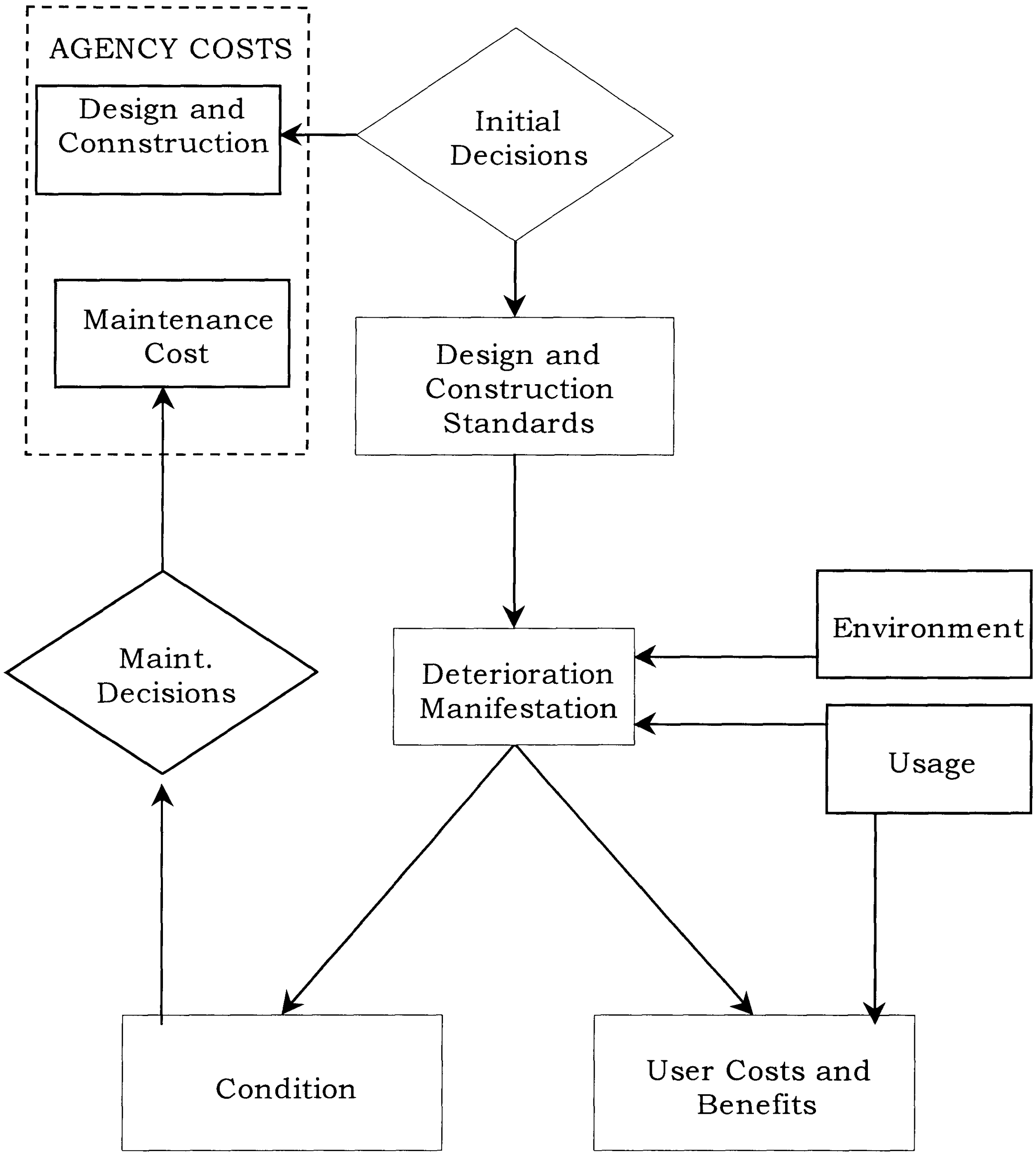


Figure 1: Infrastructure Performance Framework

For example, one could try to associate variations of infrastructure maintenance costs to the level of initial capital spending. These early decisions change the composition of the facility and, hence, the way it reacts to deterioration. This, in turn, influences the cost of maintenance incurred by the agency.

On the other hand, one could envision a more disaggregate perspective that considers the deterioration process itself in greater detail. In this deterioration-based approach, capturing the influence of construction and design standards on the condition itself could yield more explicit knowledge about the relationships of interest. In road deterioration, for instance, it would be interesting to model the impacts of changes in asphalt composition on crack development, given certain usage patterns.

Hence, these two perspectives constitute two complementary approaches to the problem. The cost-based approach investigates aggregate relationships, whereas the deterioration-based approach examines deterioration explicitly. Combining both allows to both have intricate knowledge about the underlying degradation process, though still guaranteeing a common measure to all parties interested in the outcomes of the predictions.

1.4 CONTRIBUTIONS

In this thesis, the problem defined previously will be addressed through the two approaches outlined in the above section. Though not providing a comprehensive model to predict the impacts of changes in causal variables on infrastructure performance, this thesis intends to lay the ground for future studies that will reach that goal. The contributions of the thesis, therefore, include:

- Presenting a framework to address the problem of assessing the sensitivity of infrastructure performance to initial conditions,

- Specifying a cost-based approach to address the sensitivity question

- Specifying a deterioration-based approach to address the sensitivity question

- Demonstrating the cost-based approach through a Light Rail case study

- Demonstrating the deterioration-based approach through a Bridge Deck case study

- Understanding the specifics of deterioration including the variables that influence it and the extent of this influence through the case studies

- Understanding the issues relevant to Rail Rapid Transit in order to lay the ground for being more specific in associating the findings to Tren Urbano.

1.5 THESIS ORGANIZATION

The thesis is organized as follows. In Chapter 2, the conceptual framework of our study is presented. This framework explains and analyzes the trade-off at hand and introduces in greater detail the approaches that can be followed to address the problem.

Chapter 3 then presents the Cost-Based approach. Based on a Light Rail case study, this analysis is geared at providing a broad perspective on the problem. Though based on strong assumptions, it presents the aggregate picture of the deterioration process, relating yearly maintenance expenditures to changes in initial capital cost.

These results are then complemented by the Deterioration-Based approach presented in Chapter 4. Relying on a Highway Bridge-Deck case study, this more detailed analysis links causal variables to deterioration over time. This is aimed at providing more explicit insight into the deterioration process itself.

In Chapter 5, the possible applications of the results are then discussed. The Tren Urbano context is used to give more concrete examples.

Finally, Chapter 6 summarizes the conclusions of the research and presents future extensions and directions for further research in this area.

CHAPTER 2

CONCEPTUAL FRAMEWORK

The conceptual framework focuses on the potential importance of the decisions that need to be made up-front for capital- and maintenance-intensive infrastructure projects. It discusses the relationships that occur during and revolve around the deterioration process. These relationships are, for example, how design decisions influence maintenance requirements and costs, or how deterioration affects agency and user costs. The aim of this chapter is to present how the infrastructure sensitivity problem discussed in section 1.1 is approached. In the first section, the planning, design, construction and operations management process is discussed. There, we present a logical chain of influences. Then, we discuss the maintenance versus capital expenditure trade-off by discussing life cycle costing and the effects of delayed maintenance. This helps us motivate the sensitivity analysis, which we will define more accurately in the third section. We well also introduce the elements of the methodology in the fourth section where the solution approaches to address the problem are presented.

2.1 OVERALL PLANNING, DESIGN, CONSTRUCTION, AND MANAGEMENT PROCESS

This section presents the logical framework that links planning, design, construction and operation decisions and activities to agency and user costs and benefits via physical processes. The framework is presented in Figure 2. It is organized in three distinct columns. The rightmost column features decisions inherent to the provision process. It includes planning, design and maintenance related decisions, and what constraints them, namely budget availability. The middle-column includes the activities performed and physical processes that take place throughout the provision and operations periods. Construction, deterioration and maintenance are influenced and influence decisions and costs relative to them. In the leftmost column, costs resulting from the activities and processes are shown. These activities, processes, and costs are then linked to their aggregate results, namely Useful Lifetime and Life Cycle Cost.

The essence of this framework is the relationships that exist between different planning, design, construction and maintenance issues, and how they interact with the users and the agency in charge of the operation. The activities and decisions relative to these tasks are spread across the life of the project, which is the timeframe between the planning stage to the actual replacement of a facility.

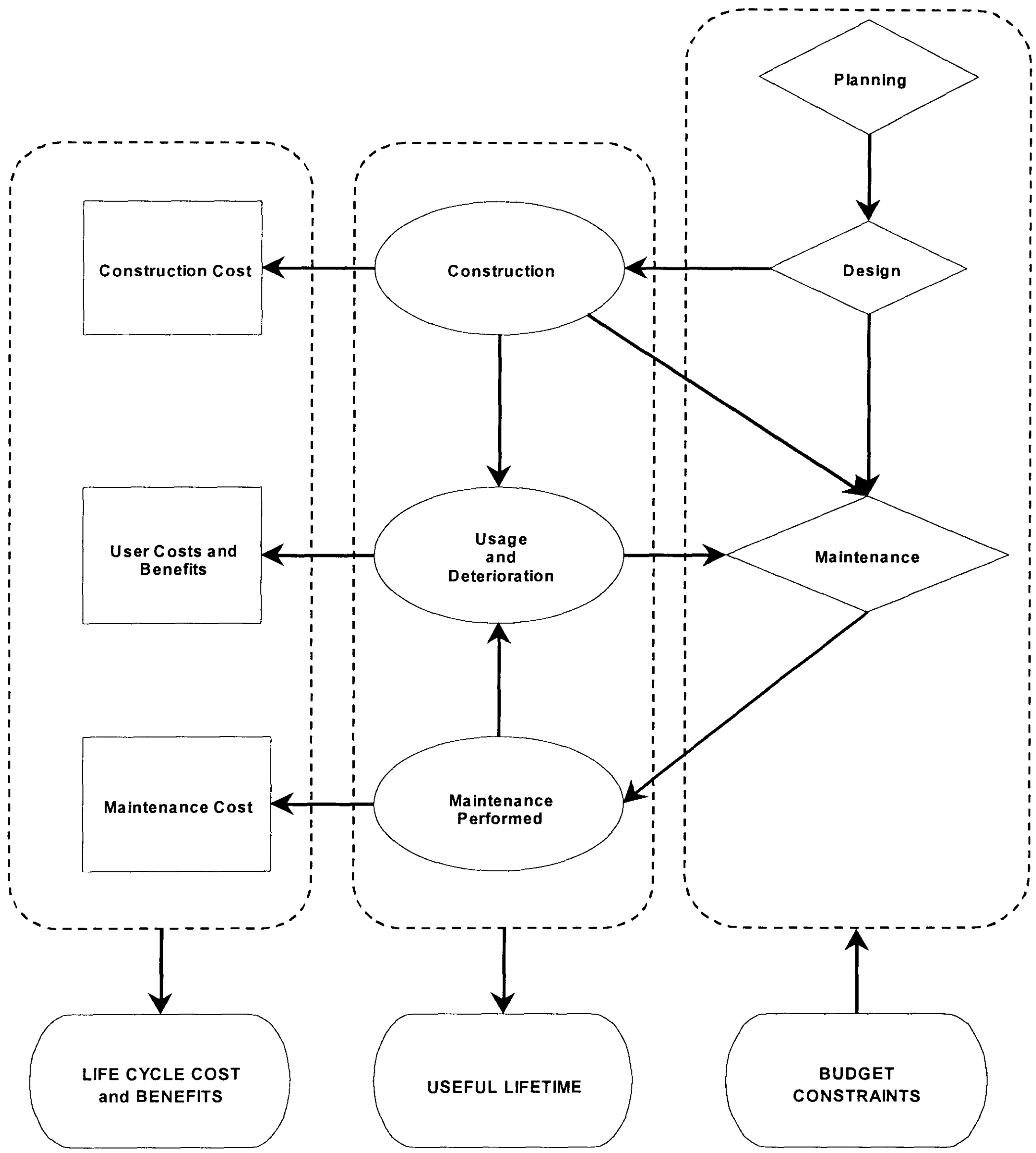


Figure 2: Relationships between Infrastructure Provision and Management Decisions, Physical Process and Costs

Typically, the starting activity is the planning stage depicted in the upper-right corner of. During this period, the needs that the facility will have to fulfill are laid out.

This stage defines very important elements like capacities, expected useful life, construction and operations budget. It also rules out solutions not acceptable to some parts of the population. There, questions like "Should the Rail Rapid Transit System be underground, elevated or at grade?" are answered. This critical phase determines in great part the magnitude of the expenditures that will be incurred. Even if there still remain a lot of factors influencing the final construction cost, the range is determined by the solution adopted during the planning phase. For example, if a subway has to be set underground to go through an area, the expenses related to this decision are 20 to 25 times higher than if an at-grade solution had been adopted (Booz-Allen & Hamilton, Inc., 1991).

The results of the planning stage have a direct influence on the design phase. The designers lay in blueprints the requirements handed to them by the planners. During the design phase, the decisions are taken at a higher level of detail. For example, the structure of a bridge can be decided upon and the plans drawn. Steel or concrete? Simple concrete or continuous prestressed? Those are the types of detailed questions that are answered at this point. Design related decisions affect two other elements of the framework. First, the maintenance requirements are a consequence of the design that has been chosen. Steel or concrete designs have very different maintenance implications. One would be monitored closely for corrosion, while the other would be monitored for cracks and spalls. The construction activity is the second element affected directly by the design decision for it is the phase that implements this design.

The construction activity is the execution of the design on the site. Therefore, construction is a direct continuation of the design. The design itself and the quality of construction are two aspects of construction that can be considered separately. The design component of the construction is probably what determines the major part of the construction cost. Quality of construction also affects the construction costs through choice of materials and contractor. For raw materials, there is usually a high correlation between quality and cost. The better the quality, the higher the cost. Furthermore, the choice of contractor will determine in great part how well the design is implemented. This will have a slight impact on the construction cost, but more importantly it will influence how the facility will deteriorate. For example, if the contractor is negligent when pouring the deck of a bridge, the concrete might not set correctly and be an early source of cracks and spalls.

We now reach the central component of the framework presented in Figure 2. The actual construction of the facility and the quality of its provision influence usage and deterioration. They are also affected by the maintenance intensity and scheduling that the system is subjected to. This matter is discussed in greater detail in section 2.2. Usage results in benefits to the user. Usually, if the facility is serving its purpose, the users are better off with it than without it. These benefits can be quantified in dollars by assessing the gains in travel time to the population and the greater access new sectors of the population may acquire resulting from the opening of a new road, for instance. Also, the reduction in air pollution consequent to a new subway system provides air quality benefits. However, these benefits can be compromised by costs caused by the decay of the facility. For example, if a road is in a bad condition, it not only causes losses of time to the users, but also increases the hazard of accident occurrences and the vehicle maintenance expenditures as well.

Another element impacted by usage and deterioration is maintenance. Typically, the worse the condition and the higher the usage, the more maintenance is required to keep the facility at an acceptable performance level. Design also influences how much maintenance is required. The type of asphalt surfacing chosen for a road will be one of the factors determining the maintenance required under normal operating conditions. Another important component to take into consideration when making the decision about the maintenance level is the budget available. The amount of money that can be spent will determine to a great extent how much maintenance the facility will receive each year.

Maintenance mostly influences the condition of the facility and its deterioration. Since maintenance activities consist of repairs and defect prevention it not only decreases the deterioration rates but also affects usage levels and user benefits as a result of better services. However, maintenance also has a cost. This cost will be a direct consequence of maintenance intensity and quality. Hence, the more maintenance is performed, and the better it is performed, the costlier the activity is.

Finally, as presented in the lower portion of Figure 2, all cost figures add up to the Life-Cycle cost and benefits. This generalized "cost" is thus composed of the construction, user and agency cost, and the user benefits. To the initial capital investment (construction cost), the user and maintenance cost figures are added in a discounted value over the predicted useful lifetime of the infrastructure. This useful lifetime is the overall result of all activities and processes including construction, usage and deterioration, and maintenance. The construction changes the useful lifetime through its design component and through the quality of the work performed by the contractor. Likewise, deterioration and maintenance, act throughout the life of the facility and influence it by determining when major rehabilitation or reprovision is required.

As can be seen in Figure 2, the framework elements are all offsprings of choices of design and construction methods and standards. The planning process provides the assurance that the facility meets the expectations and needs of the users, as well as the financial resources of the communities. Nevertheless, we do not know how much effect the planning and design decisions, and the construction quality will still have on the Life-Cycle cost and on the useful lifetime. This is the major objective of this research for we are interested by the sensitivity of the outcome to these factors. This question is in part motivated by the budget constraints that exist on many infrastructure projects. In the course of the decision making process, choices have to be made concerning the relative shares of capital and maintenance expenditures. Since the condition of the infrastructure is in part a consequence of decisions and activities taking place in the early stages of the provision, the trade-off between capital and maintenance expenditures becomes a relevant interrogation, for it falls into the category of early decisions. In section 2.2, we will try to identify some of the issues involved in this trade-off and discuss the effects of delayed maintenance.

2.2 MAINTENANCE VS. CAPITAL EXPENDITURE TRADE-OFF

Life-Cycle costing (LCC) has become a widespread tool for assessing infrastructure related expenditures over time, especially for water and transportation related projects (Arditi, 1996). The objective is to take into account all costs and benefits associated with the provision and operation of a facility over its life span in making decisions regarding design, construction, and operations management. For a given structural design, LCC is the sum of the present values of *all* expected costs and benefits, from initial construction to ultimate replacement of the facility. These costs include initial construction and design cost, expenditures for maintenance, retrofit, upgrading and refurbishment, as well as user and societal costs and benefits, and costs related to natural hazards. User costs and benefits are probably the hardest to estimate. Nevertheless, they are conceptually the most important because user benefits are the reason for which the facility is being built. Let us consider the example of a municipality that needs to raise its money for an infrastructure project through taxes among its population. If the combined cost to the users and residents (taxes, disutilities due to relocations, noise, etc.) are higher than the benefits (travel-time savings, economic benefits to the municipality, etc.), the project is not worth undertaking. Hence, the importance of benefits and costs in evaluating projects.

Thus, Life-Cycle costing allows the comparison of different investment alternatives, as well as different management policies. The goal is the minimization of this cost function, or the maximization of the benefits resulting from the provision of the new facility.

In the context of Life-Cycle costing, Figure 3 illustrates an important trade-off that needs to be assessed in making provision decisions. The figure depicts in purely hypothetical and schematic terms the evolution of infrastructure performance over time. The two influential variables are initial provision quality, which is reflected through the starting point of the curves, and the maintenance intensity and deterioration, which is translated by the slope of the curve. As discussed in Chapter 4, initial quality of provision also influences the deterioration, thus the slope throughout. For the sake of simplicity, however, the initial quality is reflected primarily by the performance level at the time of provision in this illustration.

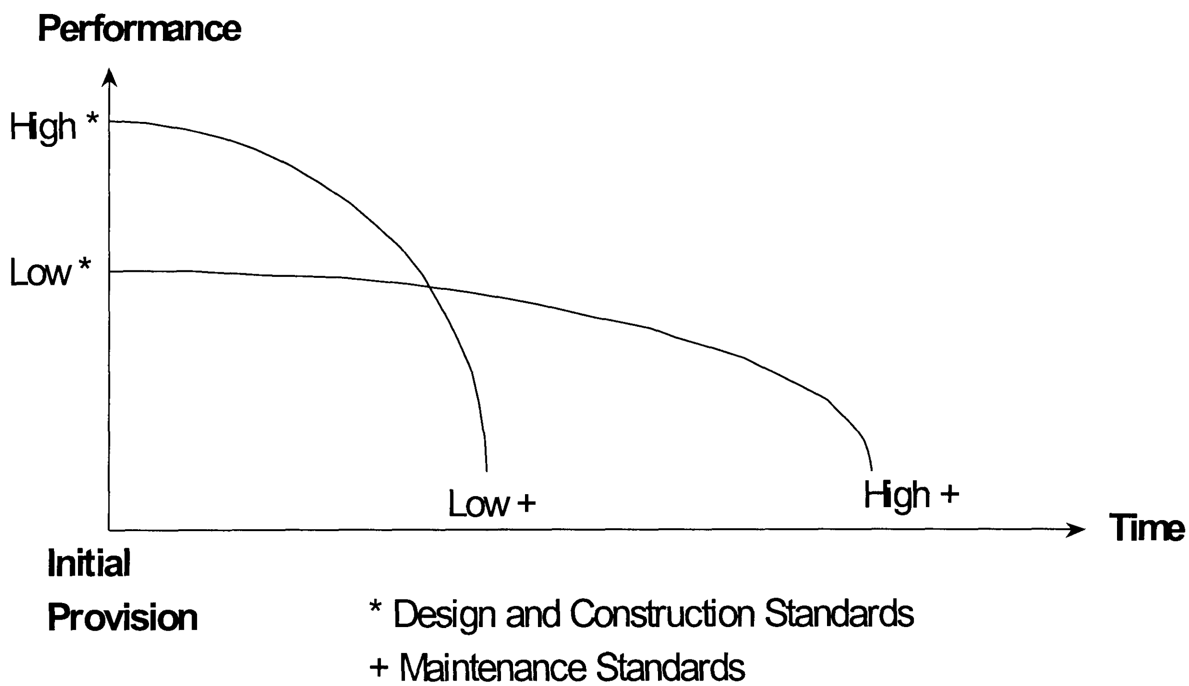


Figure 3: Hypothetical examples of infrastructure performance over time

Furthermore, the initial slope reflects the quality of construction and how well the design has been implemented in the field. The plots are also consistent with the general phenomenon that infrastructure deteriorates quicker as it ages, hence the concavity.

Figure 3 shows the evolution of two hypothetical facilities. One facility represents the case of a high initial provision standard but a low maintenance standard. The other, a low initial provision standard, but a high maintenance standard. These two scenarios are two examples among an infinity of possibilities. Conceptually, one could think of any combination of initial provision and maintenance standard. The reason why we chose to plot the performance of these two extreme scenarios in particular is to better visualize the essence of the decisions that should be made initially. The tradeoff at hand is between initial provision quality versus maintenance intensity. In financial terms, the trade-off is between initial construction and design cost versus maintenance expenditures. User costs and benefits are also part of this trade-off. If the performance is poor, user cost is going to be high.

Agency costs consist of two components: construction and maintenance costs. Construction, through design standards and quality, affects the long-term condition of the infrastructure. Of course, this is also the case for the maintenance and rehabilitation activities. Since user benefits and costs are a function of the resulting condition, the trade-off between initial provision and maintenance is not restricted to agency costs but also incorporates user costs and benefits. The higher the initial standard of provision, the more benefits the users will experience. Moreover, the better the maintenance, the longer the performance will be sustained and, likewise, the more benefits the users will have. However, expenditures are usually limited by budget constraints. Providing performance above the needs of the users is unnecessary. Furthermore, and more importantly, the budget constraint that administrations face requires that there be a distribution of the available funds on both initial provision and maintenance, hence motivating the trade-off between the quantities allocated to each of these activities. This is all the more relevant with the tendency towards Design-Build-Operate contracts that allow for integrating these three tasks under one single price. Hence, for the contractor, they all have to be taken into account simultaneously aiming for the minimum total price, while meeting the performance requirements set by the administration bidding the contract out.

So, despite the complexities that the issues of budget constraints and contractor monitoring add to the decision-making process related to the provision activities, understanding the impacts of design, construction and maintenance on the performance of the facility is a critical input aimed at increasing the efficiency of these decisions. And since activities and decisions are influenced by the decisions made at the beginning, the question of the trade-off between initial quality and maintenance is best addressed early on, because delaying it can significantly reduce the effectiveness of the consequent decision.

During the different phases of a the provision of a facility, the ability to influence Life-Cycle cost usually decreases as the process advances, as depicted in Figure 4. In general, design, even though bearing very little cost, can have great impacts on the construction techniques and materials and consequently on the construction cost. In addition, design can also have an impact on the maintenance policy that will have to be adopted over the lifetime of the facility.

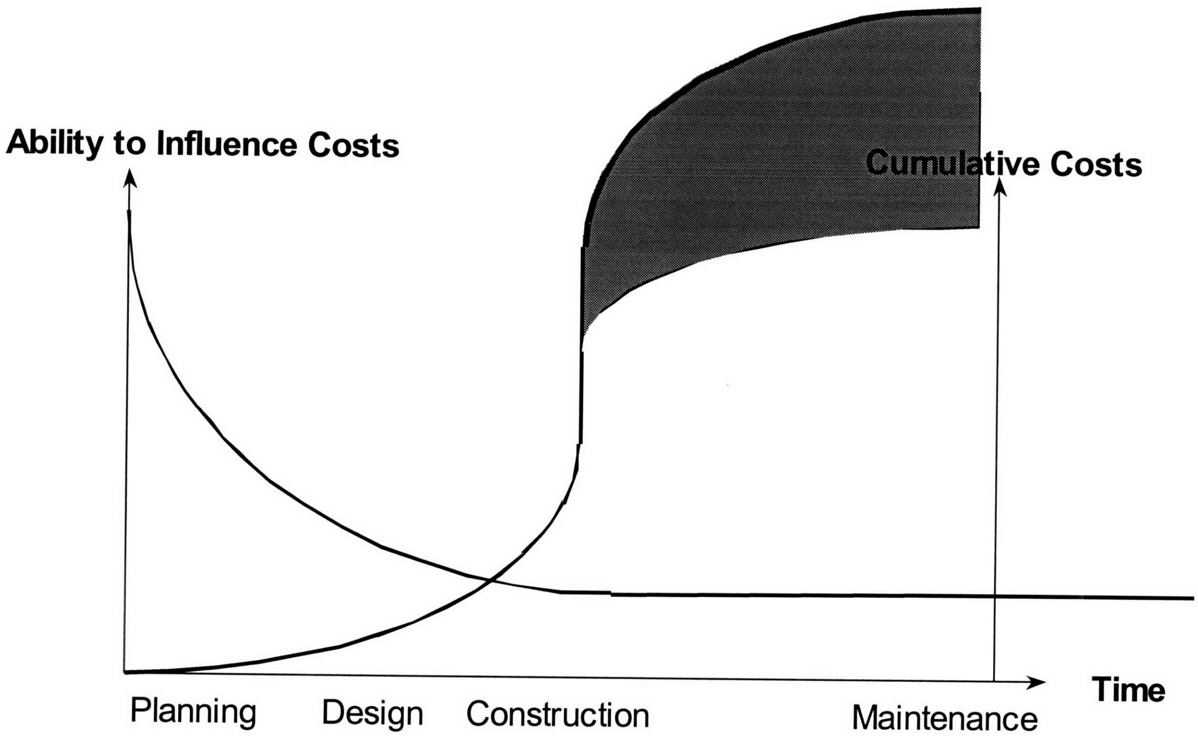


Figure 4: Ability to Influence Life-Cycle Cost over Time

The conceptual relationships between the ability to influence costs in the long run and the cumulative spending over time is shown hypothetically in Figure 4. Planning and design are, relative to construction, quite inexpensive activities, but they are the ones that offer the greatest opportunity to influence the total cost in the long-run. During the construction phase, most of the ability to influence costs is reduced, though some savings can be achieved through innovative construction methods. Nevertheless, the construction phase is the period that is the most capital intensive, causing cumulative spending to increase abruptly. This is represented by the steep increase in the slope of the plot of cumulative spending. Finally, during the maintenance period, the ability to influence costs is somewhat further reduced on an annual basis. So is the actual annual spending, thus reducing the slope of increase in cumulative spending. However, the influence of maintenance, summed over the years is fairly important, and the cumulative impact still offers a wide range of variability. Thus, maintenance decisions deserve adequate attention too.

Delayed maintenance in particular, can become a critical event. Though the effects might not be felt immediately, the long-term consequences of putting off certain maintenance activities might be significant in terms of useful lifetime remaining to the infrastructure, the quality of the facility, and rehabilitation needs in the future. It is more likely to delay maintenance in the early years of the life of the infrastructure because deterioration is very slow and unobservable, as can be seen on the hypothetical plots of performance over time in Figure 3. Hence, the effects of delaying maintenance are not felt immediately. Nevertheless, this delay usually results in the deterioration process to progress more rapidly than it would have otherwise. This leaves the infrastructure in a state where it provides unacceptable performance before initially intended. These maintenance delays oftentimes happen when budget cuts need to be made. But as shown by Figure 4, the yearly savings achieved by the consequences of such a decision are low, while the cumulative effect (as shown by the shaded area) might be significant and in the long-term superior to the short-sighted savings. Thus, knowing how a delay in maintenance affects the long-term performance and costs is important to the decision-maker. This research also contributes by gaining greater knowledge on the sensitivity of performance to different maintenance policies.

Hence, the two times where the ability to save on the costs and increase the benefits to the users are substantial, are the planning and design period, and the maintenance period as a whole. The decisions taken during the very early stages of the provision concerning design and construction as well as the decisions made during the operations period, regarding maintenance offer the opportunity to enhance the overall provision process over the life of the facility. Thus, this research contributes necessary inputs to determining how to make the best out of this process by examining the sensitivity of performance relative to the various causal factors of interest.

2.3 SENSITIVITY ANALYSIS

A sensitivity analysis approach is adopted to assess the impact of initial infrastructure conditions, including design and construction, on the long-term performance of a facility. Generally speaking, the main purpose of a sensitivity analysis is to determine how, if at all, the outcome of a process changes when the variables that are expected to influence it, change.

There are, hence, two aspects to a sensitivity analysis:

- A qualitative aspect, that determines the interactions that exist and their direction. The question that we try to answer here is the following: Is an increase in a variable causing an increase or a decrease in the outcome, or no change at all?

- A quantitative aspect that determines the magnitudes of the changes and allows for the ranking of the different influential variables with respect to their influence on the outcome.

Thus, sensitivity analysis allows for a better understanding of the conditions resulting in a certain performance outcome, and allows for determining the variables that are critical to this outcome. What follows is a general outline of what such an analysis entails.

The first task is to define the outcome of interest in a measurable way. Depending on the variables at hand, proxies may have to be used. These proxies should relate to the information that needs to be extracted in an understandable way, making sure all the underlying assumptions are well understood. In our case, the outcome is the performance of the infrastructure after a certain period of operation. This can be modeled either by using a composite performance index based on physical condition – similar to those used in the industry for roads, bridges and the like – or approximating this performance by another variable. Using maintenance expenditures directly related to the performance of the infrastructure may, for example, be a good alternative measure. Of course, such a proxy, while not able to replace the original variable completely, should have a strong relationship to the original variable.

The second task is to make an exhaustive list of all the explanatory variables. These variables are the factors that are expected to influence the process under consideration and consequently the outcome of interest.

Having specified the inputs and outputs of interest, one of the possible methods to assess the impacts of the former on the latter is to examine a set of scenarios that will introduce sufficient variability in the input variables. This allows for a comprehensive assessment of the changes in outcome with respect to changes in the explanatory variables. The purpose is to analyze the impact of each input factor, individually and in association with others, in order to identify relationships of interest to the decision-maker. This method can either rely on hypothetical scenarios derived from field data or on data gathered from systems in operation. In this thesis both forms of data are used in two separate case studies as will be discussed subsequently.

2.4 SOLUTION APPROACHES

2.4.1 INTRODUCTION

The factors that matter when considering infrastructure performance are initial provision, usage and deterioration. As shown in Figure 5, construction, usage, and deterioration combine to determine deterioration rates and resulting costs. Provision comes forward through two elements: design type and quality, and construction quality. The design type is the result of the planning process, when general concepts and needs are specified. Design quality is a reflection of how much effort is then put into applying the previous decisions to the project. Quality of construction is the representation of how well the design has been put to work, and how it has been translated into the actual system via quality of workmanship and materials.

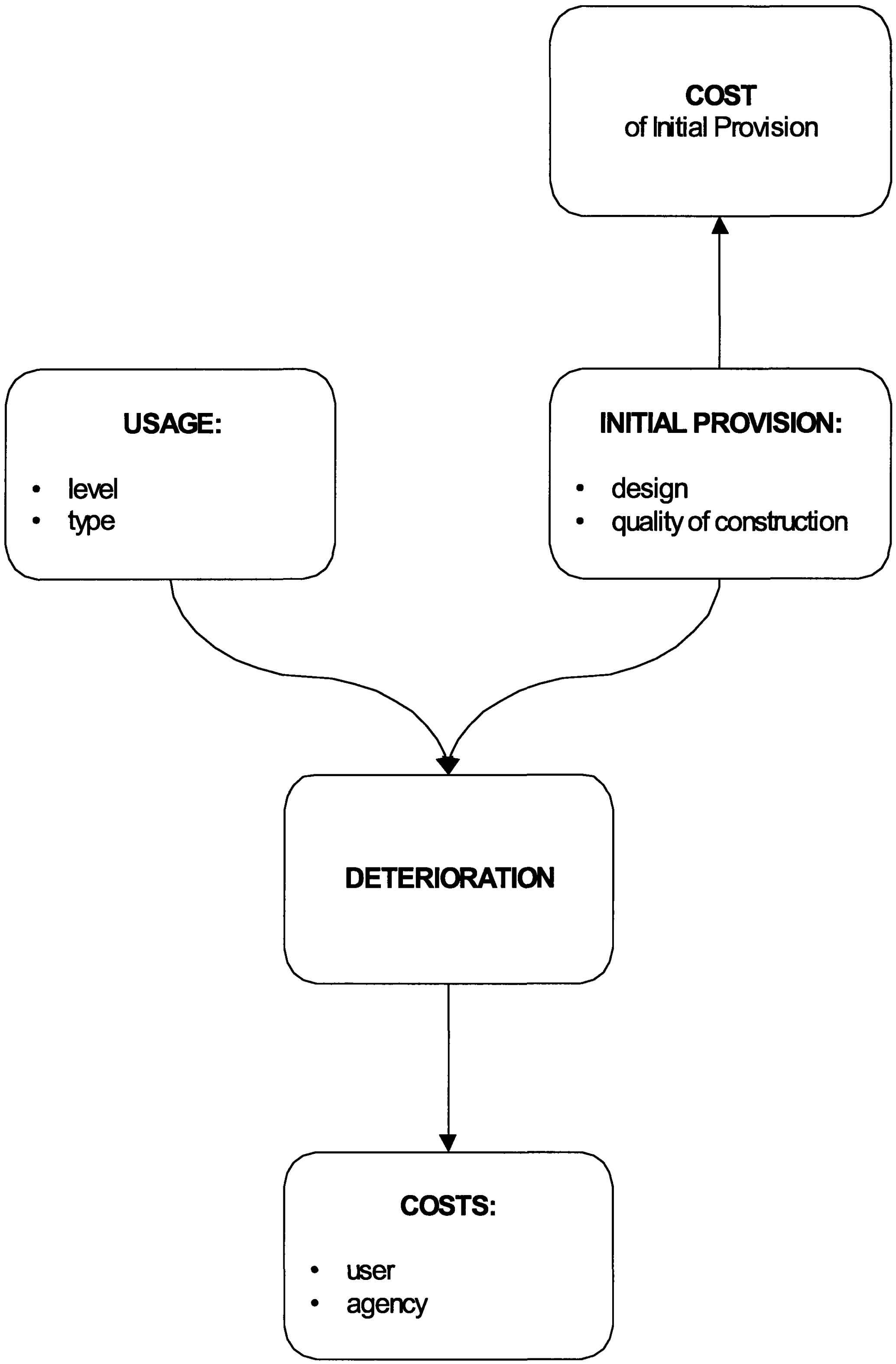


Figure 5: Effects of Provision and Usage on Costs

Usage, on the other hand, is identifiable through two characteristics: intensity and quality. Intensity reflects the level of usage, that is the physical strain on the infrastructure. This could be measured through, for example, number of car units, Million Gross Tons or number of axles over a certain period of time. Quality on the other hand characterizes the type of usage, which in turn can be translated into expectations in terms of performance. Passengers or freight, type of vehicles and type of industry are all characteristics that influence the requirements that the infrastructure has to meet.

The interaction between initial provision and usage result in two subsequent outcomes. The first is the deterioration itself as influenced by the initial provision and usage characteristics. The second is the costs resulting from this deterioration. This includes the cost the user bears due to the worsening condition state of the infrastructure. It also includes the cost the agency in charge incurs in maintaining the facility to avoid high user costs.

In order to achieve our objectives, two approaches were hence considered. Based on the framework presented in Figure 5, we can consider two levels of analysis. The more aggregate level considers the two extremities of the framework and uses only cost variables to determine the sensitivities of the performance to initial provision factors. The second approach is more closely based on the deterioration process. The central portion of the framework shown in Figure 5 represents the deterioration-based approach which is based on the direct relationships between deterioration on one side, and initial provision and usage variables on the other. In the remainder of this chapter, we present these two approaches.

2.4.2 COST BASED APPROACH

This approach considers the aggregate level. Here we examine how infrastructure performance, modeled through the costs that it generates, can be related to initial provision standards as measured by initial provision cost. The major advantage of this approach is the fact that it presents aggregate cost relationships, which are more closely related to the Life-Cycle cost and hence most useful to the decision-maker.

On he other hand, this economic analysis being at a high level presents the disadvantage of aggregating too many effects together. Also, there is an inherent difficulty related to these cost variables. They need to convey enough information on the quality of provision, the intensity of maintenance and performance levels to allow for determining the sensitivities. This data is not easily accessible because agencies usually do not systematically keep track of a record of expenses detailed enough to allow for the extraction of initial provision quality related cost variables, to capture maintenance-related costs specifically related to infrastructure condition. Furthermore, calculating user costs is a difficult task. Though some official guidelines exist on how to determine benefits to the public—EPA requirements for instance—there is no universal and accurate way of determining user costs and benefits.

So, though the perspective offered by this aggregate cost approach deals with the variables that are most relevant to the decision-makers, determining the sensitivities is rather difficult because of the lack of accurate detailed cost data on infrastructure facilities. This results in the use of a coarse model. Hence, this causes an inability to model important relationships, such as the impact of initial quality of provision on user costs and benefits, and consequently resulting in limitations in assessing sensitivities accurately and comprehensively. The disadvantage of this approach is, therefore, addressed by also adopting a less aggregate approach that would allow to model all these relationships of interest more explicitly.

2.4.3 DETERIORATION BASED APPROACH

At a less aggregate level, we introduce variables that would explain the behavior of infrastructure deterioration. Through this method, condition states and their evolution are explicitly represented, allowing for capturing the underlying relationships of interest. This analysis at the deterioration level can, consequently, be related to the cost level of interest to the decision-makers.

The major advantage of this method is that we are dealing with the deterioration process itself. We use disaggregate relationships with variables reflecting design choices, usage conditions, and maintenance policies. We actually model the evolution of condition states over time, as well as specify values of influential factors creating a wide range of scenarios thus allowing for testing of sensitivities under different situations. The accuracy that we gain by modeling the actual condition of the infrastructure is crucial in determining the sensitivities of performance to initial provision variables. This constitutes the first step of the analysis. To be completely useful to the decision-maker, this approach needs to be aggregated to the cost level by using cost relationships linking facility condition to user and agency costs, and linking initial provision scenarios to their respective costs. However, this second step is not within the scope of this thesis and is reserved for future research. Nevertheless, results about sensitivity at the deterioration level presented in this thesis should be read keeping these links with the aggregate cost variables in mind.

We used two case studies to demonstrate the two approaches aimed at assessing the sensitivity of infrastructure performance to initial provision standards. The first case study uses Light Rail cost variables and explores the aggregate cost relationships that exist between the cost of providing a facility and the cost and benefits to user and agency resulting from the condition of the system. The second case study models Highway Bridge Deck deterioration directly. It explores, at a more detailed level, the relationships between initial design and construction variables on one side, and infrastructure condition over time on the other.

CHAPTER 3

COST BASED APPROACH: LIGHT RAIL CASE STUDY

In this section, we will discuss in more detail the cost-based approach and its application to the Light Rail transit infrastructure. The results and their possible interpretation are presented. This analysis considers aggregate cost relationships between costs of initial provision and costs related to the consequences of deterioration. The nature of the results and the constraints of the analysis serve as motivation for the deterioration-based approach and its application which is presented in Chapter 4.

Since the application presented in this chapter is based on a Light Rail data set, background on rail infrastructure is first provided in section 3.1. We then introduce in more detail the cost-based approach in section 3.2 which leads us to the methodology that we present in 3.3 and use in 3.4 during the empirical analysis.

3.1 BACKGROUND ON RAIL DETERIORATION

Deterioration of infrastructure without proper maintenance can lead to lower levels of service and subsequently to potential hazards. For example, in the case of track infrastructure and train operations, derailments are life-threatening accidents that can occur because of tracks that are out of alignment or rails that are worn out and do not support the vehicles correctly. If no appropriate measure is taken, accidents are more likely to occur because of the degradation taking place.

However, maintenance activities are very costly. Whether they be preventive or repair oriented, the costs involved are quite high when one considers Life-Cycle cost assessments. The figures speak for themselves (AAR, 1987): yearly maintenance costs for the freight industry represent B$4. Therefrom, 40% are for infrastructure (B$1.6). This represents 18% of Operating Expenses (B$9).

These numbers reaffirm the importance of the background behind our objective: assessing the trade-off between initial design and construction costs, and maintenance costs, and consequently determining factors that have an impact on the Life Cycle Cost.

In addition, and especially in the case of Urban Passenger Rail, rail performance has great impact on elements that are not easily quantifiable in dollars, like ride quality, safety and impact on adjacent communities. These elements need to be considered when assessing the costs of the facility. So, the physical process of infrastructure deterioration is not the only element that deserves attention. Some other aspects that we need to be aware of at include:

- Cost and ease of maintenance.
- Ride Quality.
- Safety due to infrastructure (derailments, collisions, etc.).

These issues are very important and deserve extensive attention. Nevertheless, they are out of the scope of our study.

In this section, rail deterioration is presented through the types of failures that typically occur, the maintenance practices to alleviate this deterioration and a discussion on the relevance to passenger rail. The cost based study presented in the remainder of the chapter will not rely explicitly on the variables and relationships discussed in this section.

3.1.1 DETERIORATION

The focus of our study, deterioration, takes many aspects and representing it is not always easy. We will now present some deterioration models that are used to make predictions about the condition of each track component and distress type: rail wear, rail fatigue, the deterioration of cross ties, fasteners, ballast and subgrade as well as impacts of concrete slabs (AREA, 1996).

Rail Wear

Rail wear is certainly one of the most observable manifestations of deterioration. It is characterized by the rail's loss of profile due to excessive friction between the rail and the wheel. A comprehensive rail wear model is the one used by TRACS, in a module called RAILWEAR (Shughart, 1989. This model considers two kinds of wear.

The head wear is associated with stress on the head of the rail due to heavy wheel loads. This type of wear is characteristic of tangent or low curve track. The wheel is in a 1-point contact, and the wear will depend on the normal force acting on the rail. Usually, this type of wear is largely dominated by fatigue deterioration. In other words, fatigue failures appear before any substantial wear has occurred.

The gauge wear is a more common cause of replacement and occurs in elevated curves. Usually in a 2-point contact (one at the top of the rail head and one on the side), with a much bigger intensity due to the centrifugal force, the interaction is quite important. Lubrication and grinding, as will be discussed in section 3.1.2, help keeping this wear down.

There are various factors affecting rail wear rates. Among them:

- Curvature;
- Speed;
- Wheel load;
- Cumulative MGT;
- Maintenance practices: grinding and lubrication;

- Steel characteristics (hardness, weight).

Furthermore, assessing the influence of these variables (and others) on the value of the rail wear would be of interest in assessing the sensitivity of deterioration to parameters related to early conditions. This is not, however, the focus of this chapter and case study.

Rail Fatigue

Rail fatigue is another important factor causing rail replacement, especially on tangent track. Because this deterioration process is hardly known and is highly stochastic, empirical models are the most suited for defect prediction. The PHOENIX module from TRACS predicts rail fatigue (Shughart, 1989). We also considered an empirical approach to the problem, using statistical estimation to predict rail fatigue.

Fatigue failures are initiated by the imperfections of materials (e.g. manufacturing imprecision, material's non-perfect homogeneity) or by small cracks inside the material. These cracks grow due to repeated loads applied to the material, as a result of cyclic plastic deformation. The two major types of defects of fatigue failure are transverse defects (TD) along the cross-section and split head (SH) defects along the longitudinal axis. Consequently, the PHOENIX computer model concentrates on these two.

There are various variables affecting rail fatigue. Among them the following are included:

- Maintenance practices (grinding, lubrication);
- Traffic characteristics (wheel load, MGT);

- Deterioration due to other distress conditions (rail wear, deterioration levels of tie and ballast);
- Material characteristics (rail size, strength, stiffness);
- Track geometry (curvature, alignment, gradient);
- Factors affecting wheel-rail contact (e.g. curvature, speed, rail crown radius, wheel size, wheel profile radius); and,
- Other location and environmental factors (strength and drainage of soil and rocks, climate, etc).

Combining field and laboratory data has the advantage of compensating the respective disadvantages of each method: lack of variability of certain parameters and/or inability to measure true value for field data, inability to reproduce certain conditions in a laboratory for lab data.

Finally, it is important to point out that fatigue is very often in competition with wear. Depending on the conditions, one or the other will be the reason to replace the rail. For example, on tangent track fatigue defects dominate, whereas in curves, gauge wear is largely dominant.

Ballast and Roadbed

Ballast and roadbed are crucial track components to monitor, because the cost induced by their degradation are enormous due to the price of the components themselves, and the cumbersome activities related to their rehabilitation.

TIELIF and SURLIF are two models that predict the remaining life of cross ties and ballast. They are part of the TRACS package for predicting Freight Rail deterioration (Shughart, 1989). They are built around various explanatory variables.

The variables affecting the deterioration of the roadbed and ballast are sometimes hard to control. They include:

- Drainage (or amounts of excess water);
- Stability of slope;
- Inches of rainfall; and,
- Physical and chemical integrity.

Even if there is no precise model to predict ballast and roadbed deterioration, their manifestation is understood, as well as the variables affecting them.

Some defects related to ballast and roadbed deterioration include:

- Damping;
- Loss of stability and Erosion;
- Displaced roadbeds (variable layers);
- Ballast pockets (ballast resurgence); and,
- Fouled ballast (water table migration and pumping of the subgrade and roadbed materials into the ballast section)

Sometimes, the consequences of such defects can be life-threatening. They include:

- Loss of line (track is not horizontal anymore);
- Vertical and lateral displacement (loss of alignment); and,
- Train derailments.

The treatment of these consequences after their occurrence is usually very costly and disruptive. Thus, it is necessary to be able to predict condition accurately, in order to take preventive measures.

Other Track Material

Other track components need monitoring too. Among them:

- Ties (wood and concrete);
- Fasteners; and,
- Slabs.

Here again, no precise models are available. But the variables are also explicit, and their effect understood. And even if the impact of certain variables is not quantifiable, a qualitative approach often allows predicting reasonable ranges of variability.

3.1.2 MAINTENANCE PRACTICES

Maintenance practices also have a lot of impact on deterioration rates. Quantity and quality of maintenance can increase life up to 10 times! It therefore has to be taken seriously.

Lubrication

Lubrication can increase life in curves by 3 to 5 times in both freight and rail rapid transit (Kramer, 1996). The softer the rail, the more sensitive it is to lubrication (i.e. the higher the gains of lubrication). But lubrication needs to be monitored closely to maintain adequate levels of grease on the tracks since overlubrication also leads to increased lateral forces and wear.

One consequence of lubrication is that due to the reduction in wear rates, rail fatigue can become the dominant replacement criterion. Hence, one needs to monitor for defects where they are usually not expected. Furthermore, through lubrication rail corrugation growth (rails take a wavy form) can also be dramatically reduced. It not only reduces the propagation of this exponentially growing deterioration form, but also provides much better Ride Quality to customers.

Grinding

Grinding has now become a very widespread practice in freight rail. It now also has been introduced in Transit Rail, since it yields high benefits (Kramer, 1996). Typically, grinding increases wheel life by 8 to 10 times (from 20,000 miles to 200,000 miles...). It also lowers significantly noise levels by 10 to 15% and yields fuel savings by up to 30%.

This technique is especially helpful when associated with lubrication. Furthermore, it breaks the circle of wheel-track interaction, where reciprocal deterioration speeds up the degradation process: the wheel wears the track out of profile, which in turn wears the wheel out of profile. Finally, grinding is especially successful when performed on prerevenue rail, because it does not allow the previously mentioned circle to start at the time when the track is put in service.

3.1.3 RELEVANCE FOR TRANSIT RAIL

While deterioration rates are very important for freight rail, they are less important for transit rail, mainly because of the lesser loads the tracks have to sustain. However, the consequences of deterioration are felt earlier in transit rail. A slight worsening of the physical condition of the tracks might be felt significantly by passengers, especially at high speed, whereas low speed bulk merchandise trains would not be affected.

What is important is not that much the physical condition of the track but the performance as it relates with the impacts of deterioration on the following:

- Vehicle (wheel profile wear);
- Passengers (ride quality, noise, allowable speed);
- Adjacent communities (noise levels during operation and during night maintenance);
- Safety (allowable speeds, risks of derailment or collision); and,
- Public image of the system
- Maintenance Costs. Impact of very limited track availability and/or out-of-service work hours on cost to maintain.

3.2 APPROACH

As discussed in the previous chapter, in the cost-based approach we are only considering the economic level where the explanatory variables and the performance outcome of interest are approximated through cost measures.

This approach is motivated by several reasons. It offers the opportunity to use directly the variables relevant to the decision-maker. Furthermore, in Figure 5 of section 2.4, we consider the two cost extremities of the framework depicted. Thus, there is no need to model the relationships existing at a higher level of detail, and we can rely solely on the sensitivity of Life-Cycle cost to variations in initial provision costs. For example, we relate maintenance expenditures to system construction costs in order to determine the sensitivity of condition to initial provision.

In this chapter, we will be considering the effects that construction and design expenditures and usage have on maintenance costs. We used data from five recently built Light Rail systems across the US. The intuition behind this approach can be explained by going back to the conceptual framework developed in section 2.1. Planning and design decisions result in a certain initial provision, which has a certain cost. This provision, as well as maintenance decisions, influences the deterioration thus the performance of the system. This can be measured by the user and agency costs resulting from the deterioration.

In this case study, our interest is to model the effects of changes in condition, as measured by the costs related to it, through changes in initial provision, as measured by construction cost. We especially focus on the relationship between the choice of construction and design quality and method on the one hand, and the actual maintenance level on the other. These relationships capture the economic, broad-scale interactions that take place, without explicitly modeling the underlying infrastructure deterioration.

As required for an economic analysis, we used cost-data extracted from various sources pertaining to Light Rail systems in five US cities. Summary of the systems that we could gain enough information on are presented in Table 1 along with their corresponding summary.

Since construction costs vary a lot depending on the composition of the system and the different design options (e.g. at grade, elevated or subway), we need to have these costs separated. This data is provided in Booz-Allen & Hamilton (1991). Furthermore, we need the maintenance costs for these systems across the years. This data is provided in the National Transit Database (1988-1997). This piece of information represents the cash flows related to the operation of the systems and counts towards the Life-Cycle cost.

The maintenance expenditures across the years 1986-1995 is split between Vehicle and Non-Vehicle Maintenance, but not any further. So, though our interest was solely track maintenance, we could not separate it from station maintenance expenditures. Ideally, having maintenance expenditures for each type of track (elevated, at grade and subway) would have enabled us to better separate the effects of design on the outcome. But since this data was also unavailable, we had to work with the aggregate values. Another valuable information that the National Transit Database data set provides are the usage levels. They are expressed in systemwide vehicle-miles per year.

System	Year Constructed	Route Length (Miles)	Track Miles	At Grade Route Length (Miles)	Elevated Route Length (Miles)	Subway Route Length (Miles)	*Construction Cost (M$)*
Los Angeles	1991	22.6	43.6	18.3	3.6	0.6	*125.12*
Pittsburgh	1989	41.1	62.4	27.1	2.9	5.3	*163.37*
Portland	1987	15.2	29.3	9.9	5.2		*76.64*
Sacramento	1987	18.3	25.6	17.6	0.7		*46.21*
San Jose	1988	19.9	40.8	19.7	0.2		*50.09*

The route lengths do not add up to the total value because of the absence of Open Cut Route Length, which is not negligible for only one system

Table 1: Summary Statistics of the 5 LR systems

Although the compiled data set is very useful in content, the number of observations (5) is very small and hence quite limited. Therefore, the analysis should only be viewed as demonstrative and preliminary. It should not be used to arrive at conclusive findings but rather to point out to directions of further research. Furthermore, the systems are all very young of age (less than ten years). Thus, the long-term implications of deterioration might not have been felt yet, thus not reflecting on the maintenance costs.

3.3 METHODOLOGY

We now discuss the methodology used to conduct the cost-based sensitivity analysis, going through the structure of the model that is adopted, the underlying assumptions that are needed to conduct this analysis and interpret its results. Finally, the sensitivity analysis is specified.

3.3.1 MODEL STRUCTURE

A simple multivariate regression model is adopted to relate performance with design and construction standards, and usage. A cost proxy for the condition of the infrastructure performance is adopted, namely the maintenance expenditures that the agency incurred to address deterioration. The independent variables reflect the quality level of the system's initial provision (i.e. performance at delivery), which is also measured via a cost proxy, namely design and construction cost. In addition, the usage level is adopted as an independent variable as well.

As an initial model specification, a model linear in its independent variables is adopted due to lack of *a priori* knowledge that indicates otherwise. Though there are not many data points, the model's results offer interesting trends, setting the stage for further exploration and analysis.

3.3.2 ASSUMPTIONS

Certain assumptions are made by virtue of the choice of variables and model specification. These assumptions, even if arguable, can be defensible under some conditions. Nevertheless, as will be evident subsequently in this chapter, some of the results can be interpreted in light of some of the limitations of these assumptions.

The first assumption is that design and construction cost variables are good proxies for initial quality. Choice of material and care in execution are factors that contribute to higher cost and a higher quality of the final product. However, other factors influence cost without necessarily reflecting on quality. Hence, cost is not always the best proxy for quality. For example, complexity sometimes overshadows this quality component. Complexity of design and, consequently, of execution add to the cost without necessarily adding quality to the infrastructure in terms of its deterioration. This is particularly the case when complexity of design is needed to address certain context specific constraints relating to the location of the facility for example.

The second assumption is that maintenance activities and, consequently, costs respond to the needs of the system, mirroring its condition. That is, the more a facility is deteriorated or prone to deterioration, the more maintenance is performed. However, maintenance decision making may not proceed in this fashion due to the influence of other factors. For example, budget constraints may have serious impact on maintenance expenditure. Also, different agencies may have different maintenance standards resulting in different maintenance activities and expenditure for the same condition. Therefore, this assumption is not always valid, and its consequence is inappropriate maintenance for the period under consideration thus affecting the overall condition of the infrastructure. Of course, this deteriorated condition would clearly not be reflected in the maintenance cost as is assumed in this analysis.

3.3.3 SENSITIVITYANALYSIS SPECIFICATION

In this context, sensitivity can be viewed in the following way. It is the differences in maintenance expenditures explained through the differences in construction and engineering quality. These relationships should reflect the trade-off that should be addressed during early decision-making as discussed in chapter 2.

The sensitivity is determined through the interpretation of the coefficients estimated using the Least Squares regression method. We are looking for several types of results as follows:

- T-statistics for a sample size of five: the Z-values of significance are 2.571 at 95% confidence and 2.015 at 90%. We will only consider coefficients that are significantly different than zero, i.e. with t-statistics greater than the Z-values at 90% confidence.

- Sign: the sign is very important because it gives us the direction of interaction. A positive sign means that the variable is contributing to increase maintenance costs, as it increases. Hence, it is contributing to faster deterioration rates.

- Magnitude: the magnitude is also important in that it provides the relative importance of variables. For example, two types of construction costs can be compared through the relative magnitude of their impact on maintenance.

With these three types of results, we are able to interpret the coefficient estimates and see if they match our a priori expectations. These expectations are presented along with the introduction of the independent variables in the next section.

3.4 EMPIRICAL ANALYSIS

In this section, the results of the case study that we conducted on the five Light Rail systems introduced in section 3.3 are presented and discussed. After discussing the variables that are used, we present the results and discuss their implications.

3.4.1 VARIABLES

In this section, we discuss the variables that we found most suitable for our study and present the *a priori* expectations that we had on their role before estimating the models. The goal behind our choice of variables is to best express the relationships that would take place. In order to do so, we made the most sensible choices for the objective of the study. For example, expenditures have to be normalized across the five systems over space and time and, therefore, choosing between expenditures per track mile versus per route length, and annualized costs versus total cost is necessary.

The first step was to choose between track miles and route length. Route length is a convenient way to measure the coverage of the system and how much total passengers can have access to it. But it is not a good normalizing variable for our purposes. Since we are exclusively interested in track infrastructure, cost and usage per track mile is by far the better way to bring the five systems to a common scale. Track mile is indeed the better option, for it takes into account the total amount of miles of infrastructure and not only the length of routes available. Hence, costs and vehicle miles are normalized by division of these figures by their respective track length.

Since the systems were built in different years, we first have to bring all the cost values to a common year. Construction expenditures, design and engineering costs were all converted to 1990 dollars.

For the vehicle and non-vehicle maintenance time series observations from the date of first operation to 1995 are available for all systems. Hence, in order to have normalized expenditures, we chose to annualize maintenance expenditures, using the discounted net present value of all cash flows and adopting 1990 dollars. This way we had a much better variable than the raw values. By taking the annualized values, we had the opportunity to take out the yearly variability. Furthermore, the annualization addresses the complication introduced by the variability in age across the five systems. Since the observations are made over different durations, we are hereby capable of comparing the cost values of the system.

The discount factor that we chose was 7%, as required by the Federal Transit Administration's Operation and Maintenance Bluebook (1991). This value has to be used when submitting calculations to support requests for federal funding from this agency. Adding 3% inflation, in accordance with the actual estimated inflation rate in the US (Brealey and Myers, 1996) brings the real discount factor to 10.21% (1.07 x 1.03 – 1) annually.

Finally, vehicle miles are averaged across the years of operation. The resulting yearly figure is then normalized by track mile. What follows is a presentation of the variables used in the analysis and their expected role. All these variables are normalized according to the discussion above. All cost variables are in Millions of Dollars (M$).

Non-Vehicle Maintenance Expenditure

This is our dependent variable. The assumption is that maintenance approximates the condition of the facility because the worse the condition, the more maintenance is performed, hence the higher expenditures. We are not able to separate track from station maintenance and have to acknowledge this limitations when interpreting the results.

At Grade Construction Cost

This independent variable is the proxy for At Grade Construction quality. With the assumption that materials and labor constitute the major part of the cost and hence offer a quite linear relation with quality. The expectation being that better quality will decrease the deterioration and therefore contribute to less maintenance expenditure. Hence, we expect a negative sign for the coefficient of this variable. This means that the more you pay for a mile of At Grade track, the better its quality and, therefore, the less one needs to pay to maintain it.

Elevated Construction Cost

The Elevated Construction cost is used in a similar fashion as the previously mentioned At Grade construction cost. The *a priori* assumption is thus the same. Nevertheless, the quality assumption is harder to sustain here, for the relationship between cost and quality is not as obvious as before. This is because elevated structures are more complex. Hence, a bigger part of the expenses are attributed to reasons such as integration in the urban context and architectural effort and not as much to quality of materials or execution, like it is the case for At Grade construction.

Vehicle Miles

This variable being normalized by track mile provides a good proxy for the usage of the system as it represents the number of times that a mile of track experiences a vehicle rolling over it. This variable is the average over all the years of operations. Very naturally, one expects maintenance expenditure and deterioration to go up with usage, thus a coefficient with a positive sign.

Engineering & Design Cost

Quality of design is very important for our purposes. This is the variable that is used as its proxy. Usually, the better the design, the more expensive it is. Nevertheless, since design production, including drafting, usually represents almost 70% of the total design bill (Miller, 1997), the relationships are not as clear-cut. This production component outweighs the quality component and makes it difficult to associate design cost to design quality. Furthermore, design complexity would also add to the cost despite the fact that it may not really add to the quality of the provision in terms of infrastructure deterioration. Nevertheless, the *a priori* belief is that better design should reduce deterioration and maintenance expenditures, thus a negative sign for the coefficient would be expected.

Construction and Project Management Cost

This variable is introduced to deal with another element of the quality of initial provision, namely the execution of the construction. Good construction and project management aims at reducing defects due to poor execution of the blueprints by the contractor. Hence, one would expect quality to be higher with better construction and project management, hence lower maintenance cost. The expected sign for the coefficient is, therefore, negative.

3.4.2 MODEL ESTIMATES AND INTERPRETATION

In this section we present the results from the linear regression model estimation. We first discuss the results concerning variables that have intuitive results, namely a sign in accordance with the *a priori* expectations. We then move on to present results that are counterintuitive and that lead to some of the limitations raised in the subsequent section. These results should only be viewed as demonstrative of the methodology explored in this case study. These results should not be used for any cost evaluation analysis, for they are preliminary illustrative results that help us evaluate the validity of the cost-based approach.

The model that exhibited only significant variable estimates is shown in Table 2. Model 1 only uses two independent variables, namely At-Grade construction cost and Elevated construction cost. Both coefficients related to these variables are significant and are interpreted subsequently. Three other models help us support the interpretation of variables that are not found to be significant, but worth comparing to their *a priori* expectation. Model 2 is presented in Table 3 and introduces a variable representing system usage, namely Vehicle Miles. Model 3, presented in Table 4 combines the two construction cost variables with the construction and project management cost variable. This allows for determining the impact of quality control on the outcome. Finally, Table 5 introduces Model 4, which features the Engineering and Design cost variable to test for sensitivity of design quality on maintenance expenditures.

Intuitive Results

Many results were in accordance with our *a priori* expectations. The constant is positive. This is because there is always a minimum level of maintenance required, independent of the technical characteristics of the system, and independent from its usage level. This value can be interpreted as the fixed maintenance cost for the infrastructure.

The coefficient for At-Grade Construction is negative in all models. This is one of the better results. The T-statistic is also significant. The sign being negative indicates the following relationship: the more is spent on At Grade track construction, i.e. the better the quality, the lower the maintenance expenditures are later on. This result is very interesting in that it supports the intuition about the existence of relationships between initial provision quality and long term performance. Figure 6 indicates this effect graphically based on the results of model 1. The strong downward sloping curve is a good indication that a relationship exists between At Grade construction quality and infrastructure performance.

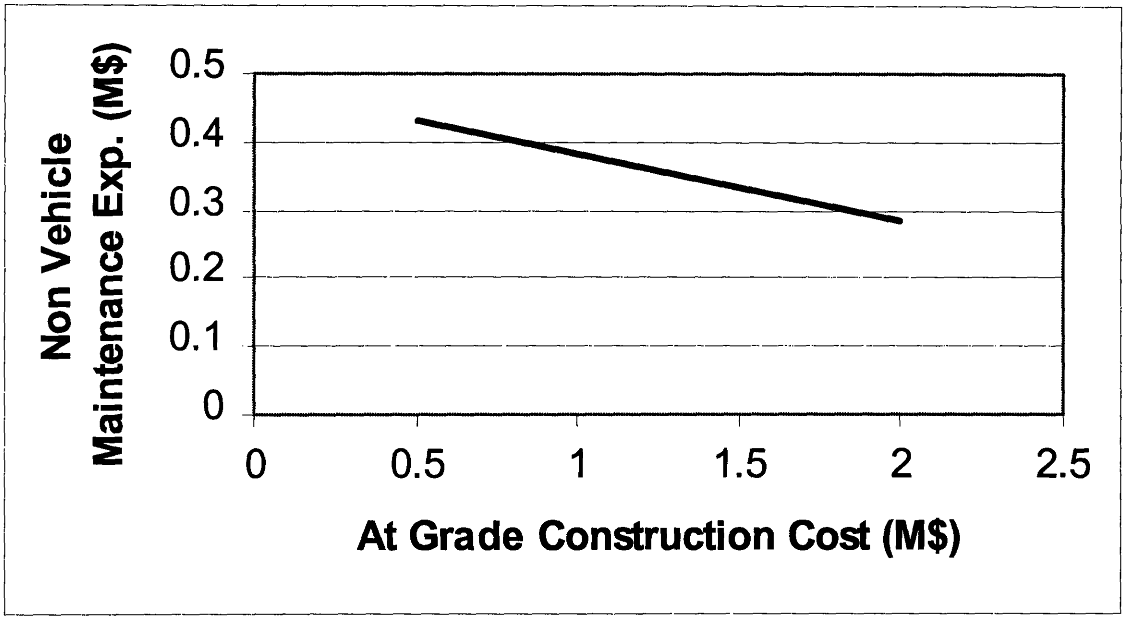


Figure 6: Effect of At Grade Construction Cost on Non-Vehicle Maintenance Expenditure

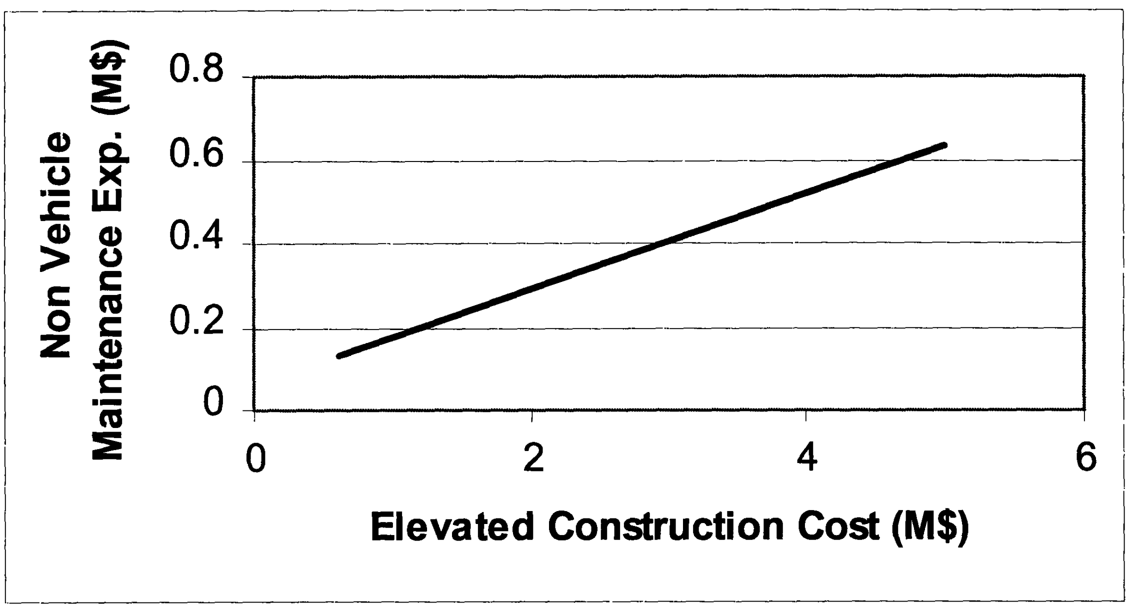


Figure 7: Effect of At Grade Construction Cost on Non-Vehicle Maintenance Expenditure

Table 2: Estimation Results for Model 1

DEPENDENT VARIABLE: NON-VEHICLE MAINTENANCE COST

Explanatory Variable	Coefficient	Standard Deviation	T-Stat	P *
Constant	0.1562	5.48E-03	28.53	0.001
At-Grade Construction Cost	-0.0716	3.96E-03	-18.08	0.003
Elevated Construction Cost	0.0957	8.15E-03	11.74	0.007
Sum of Squared Errors = 4.746E-06	R^2 = 99.40%		R^2 (adj) = 98.90%	

** P is the probability that the coefficient is not significantly different from 0*

Table 3: Estimation results for Model 2

DEPENDENT VARIABLE: NON-VEHICLE MAINTENANCE COST

Explanatory Variable	Coefficient	Standard Deviation	T-Stat	P *
Constant	0.1486	7.66E-03	19.4	0.033
At-Grade Construction Cost	0.0747	4.22E-03	-17.69	0.036
Elevated Construction Cost	0.0908	8.11E-03	11.19	0.057
Vehicle Miles	0.0003	2.00E-04	1.27	0.424
Sum of Squared Errors = 4.148E-06	R^2 = 99.80%		R^2 (adj) = 99.10%	

** P is the probability that the coefficient is not significantly different from 0*

Table 4: Estimation Results for Model 3

DEPENDENT VARIABLE: NON-VEHICLE MAINTENANCE COST

Explanatory Variable	**Coefficient**	**Standard Deviation**	**T-Stat**	**P ***
Constant	0.1636	7.55E-03	21.67	0.029
At-Grade Construction Cost	-0.0738	3.89E-03	-18.99	0.033
Elevated Construction Cost	0.1018	8.65E-03	11.78	0.054
Construction and Project Management Cost	-0.0039	3.06E-03	-1.26	0.426
Sum of Squared Errors = 4.166E-06	R^2 = 99.80%		R^2 (adj) = 99.10%	

** P is the probability that the coefficient is not significantly different from 0*

Table 5: Estimation results for Model 4

DEPENDENT VARIABLE: NON-VEHICLE MAINTENANCE COST

Explanatory Variable	**Coefficient**	**Standard Deviation**	**T-Stat**	**P ***
Constant	0.1439	6.18E-02	2.33	0.258
At-Grade Construction Cost	-0.0662	2.72E-02	-2.43	0.248
Elevated Construction Cost	0.0923	2.01E-02	4.6	0.136
Engineering&Design Cost	0.0044	2.16E-02	0.2	0.873
Sum of Squared Errors = 6.579E-06	R^2 = 99.50%		R^2 (adj) = 97.80%	

** P is the probability that the coefficient is not significantly different from 0*

The coefficient for Vehicle miles, as presented in Model 2 and presented in Table 3, has a positive sign, even though not quite significant. This is intuitively correct also, since the more the system is used, the more maintenance it requires. The fact that the coefficient is not significant, however, is also interesting.

It actually corroborates the claims of some rail professionals (Kramer, 1996). The loads in Rail Rapid Transit, unlike the case for Freight Rail, are too low to cause substantial damage. However, the slightest defect or wear can cause a significant increase in user costs, which we did not capture here, namely noise, ride discomfort, increased travel times, or safety hazards. Furthermore, variables like construction quality, maintenance practices and mere aging are usually considered the most important variables to explain transit deterioration by these professionals.

Finally, construction and Project Management Costs, which are also a good guaranty for construction quality have a coefficient with negative sign. Though not significant, this trend is also pointing in the right direction by suggesting that the more the expenditure to assure good construction, the easier the maintenance of the system is.

However, not all the results confirmed our expectations. As a matter of fact, as presented in the following paragraphs, some came out contrary to our *a priori* expectations. Though these counterintuitive results are discussed and explained, they are primarily shortfalls of the assumptions discussed in section 3.3.2.

Counterintuitive Results

The coefficient for Elevated Construction cost is significant and positive as exhibited by Models 1 through 4. The interpretation of this result is as follows: Elevated Construction cost is a better proxy for the complexity of the infrastructure than it is for its quality from a deterioration point of view. This is supported by the difficulties involved in integrating elevated structures in an urban context. This results in a high layout and architectural intricacy, which can be translated into complexity of design and of construction. This complexity most likely results in increased maintenance expenditures, since complex structures usually pose more constraints on maintenance activities. For example, access to an elevated facility where it is located in close proximity to existing structures can be quite difficult, contributing to higher maintenance costs.

Engineering and Design cost exhibits a positive coefficient, although insignificant, as shown in Table 5 for Model 4. A negative coefficient would have indicated that better design would yield lower maintenance related expenditure. This counterintuitive result, therefore, can be attributed to the complexity issue discussed above as well. Design efforts can be tightly related to complexity, and not so much to quality. This, in addition to the fact that design production accounts for as much as 70% of the design cost (as discussed in section 3.3.2) explains this result. Furthermore, the coefficient of Engineering and Design cost is not significant. This might actually point out that our approximation for design quality is not acceptable or simply that design quality does not have an impact on the deterioration of the system.

3.5 SYNTHESIS

The interpretations of the previous section are offered after thoroughly reviewing all the issues involved. Though some results were encouraging, others point to the difficulties associated with an aggregate cost-based analysis and the data set used. Hence, a more disaggregate analysis dealing with deterioration itself is further motivated and justified. In this section, a synthesis of the results is presented, leading to the justification for the deterioration-based analysis

3.5.1 RESULTS

Working through the relationships of interest in a very aggregate manner, the cost-based approach considers mainly the economic interactions that take place. The cost variables are used for approximating quality of provision (construction and design), and deterioration rates. We are trying to test the following underlying *a priori* hypothesis: the better the initial provision standard, from a design and construction standpoint, the lower the deterioration rate. Our purpose is not only to test this hypothesis, but also to determine how sensitive deterioration is to these initial provision factors. Our major goal is to see how deterioration expenditures change when the initial conditions change.

Our independent variable is:

- Non-vehicle maintenance expenditure, annualized and discounted over several years of operations. This variable was used to approximate deterioration rates and the condition of the infrastructure.

We then use a linear regression model. The following explanatory variables are explored:

- At Grade Construction cost to reflect the quality of the at grade track;

- Elevated Construction cost to reflect the quality and complexity of the elevated track structure;

- Engineering and Design cost to measure the impact of changes in design quality;

- Construction and Project Management costs that reflect the additional quality concern put into the construction of the system; and,

- Vehicle Miles to reflect the usage level.

All these variables are normalized by track mile, to be able to compare systems of different sizes.

The results confirm some of the *a priori* expectations, especially for At Grade construction. Quality as measured by At Grade Construction cost is shown to matter for At Grade Construction and does indeed reduce the maintenance cost. Usage, and construction and project management also offer intuitively satisfying results in terms of the nature of their relationship with maintenance expenditures, even though their corresponding coefficients are not significant. Maintenance expenditure grows with usage and decreases with construction and project management expenditure.

However, we also obtained counterintuitive results. Some model estimation results indicated that higher expenditure for engineering and design (although the coefficient is not significant), and for elevated construction yielded higher maintenance costs, where better quality would be expected. These two counterintuitive results are explained by arguing that these two variables are not good proxies for quality. They can be much more closely linked to complexity, especially since design quality only accounts for a small percentage in the design-related expenditure, which are dominated by design production. This increased complexity can result in higher maintenance costs, for in this case functionality and urban aesthetics may take priority over maintainability.

In summary, some encouraging results are arrived at, but also limited by the many assumptions that are associated with this cost-based approach. These limitations are further discussed below.

3.5.2 LIMITATIONS

Conceiving the model, we face limitations of two types. The first type of limitations is are data related, for we could not find data to suit our needs. The second type of limitations is methodology related and further support the necessity for a less aggregate approach. The data related problems are the following:

- Sample size: with a sample size of only 5 observations, the results should only be viewed as preliminary and demonstrative in nature only.
- Period of operation: the five facilities are still in the early stages (4 to 10 years) of their expected lives. This does not allow for considering the infrastructure up to its first major rehabilitation, which would have offered a complete cycle and hence a more comprehensive view.
- Cost comparisons: when comparing different systems to one another, we might actually not face the same

conditions everywhere. For example, the Right of Way might be cleared for some systems, while it requires additional work, thus expenses, for clearing it for other systems. Hence, the cost variables might not be consistent across the five systems considered.

Moreover, some of the assumptions that the methodology relies on are arguable. What follows are limitations that they suffer:

- Cost proxy for quality: taking costs as proxies for quality might be justifiable in some cases like at grade construction, where materials and labor intensity are more directly related to the quality of the final product. On the other hand, in other cases this assumption is not justifiable. For design and engineering costs for example, this does not apply. Since quality represents only a very small percentage of the total design cost, approximating quality through cost is not a very reasonable assumption.

- Maintenance expenditure proxy for condition: we used the maintenance expenditure variable as a proxy for deterioration. It is true that maintenance-related expenditures reflect the condition of the infrastructure. However, these funds are very prone to be subjected to budget constraints. Also, performance standards can vary from one agency to the other. Therefore, the relationship between condition and maintenance expenditure can be a weak one.

Of course, as was discussed in section 3.3.3, these limitations were instrumental in interpreting the results.

The interpretation of the results offered in section 3.4.2 have themselves their limitations. Especially, when it came to interpreting counterintuitive results based on variables whose value relies on strong assumptions. The interpretation is based on intuitive explanations and not hard evidence. Additional investigation is warranted to confirm these interpretations and explanations.

3.5.3 MOTIVATION FOR DETERIORATION-BASED APPROACH

As a consequence of all the previous limitations exposed. Pursuing another approach as above is warranted. Doing so would enable us to take advantage of some of the interesting results of the cost-based approach. Confirming them would provide further confidence in their value.

Furthermore, there is another important reason to take another approach. Performing an analysis at a less aggregate level allows us to get an understanding of the underlying deterioration relationships. This is important in that it allows us to deal with the deterioration itself and, more importantly, with factors that influence it. Since the deterioration-based approach is considering a more detailed perspective, we can really concentrate on what causes the different costs to vary. Moreover, this method uses a model that allows for the prediction of outcomes of hypothetical scenarios that we can specify. Hence, this enables the introduction of variabilities that do not need to be observed in real data. The outcome is computed from the inputs to the model. Thus, we can observe more variations in variables than what we would have gathered from real field data. Furthermore, with the addition of cost models, this method can be built up to the aggregate level, thus serving a similar purpose to the decision-maker as the cost-based approach.

CHAPTER 4
DETERIORATION BASED APPROACH: BRIDGE DECK CASE STUDY

4.1 INTRODUCTION

The cost-based approach to the sensitivity problem already gave us some good insights on how initial conditions might impact long-term infrastructure performance. Especially, the relationship between At Grade construction quality (as measured by cost) and infrastructure condition (as measured by maintenance expenditures) was particularly valuable. However, because of the many shortfalls of this method, the numerous assumptions that are made, and the difficulty of offering conclusive interpretations of the results, deterioration-based approach for addressing the question of sensitivity of infrastructure performance to initial conditions is also pursued.

Because of the lack of deterioration data on Rapid Rail Systems, we chose to draw a parallel with another infrastructure system where condition is also closely monitored, namely highway bridge systems. There is no immediate parallel as far as specific conclusions that can be drawn between the bridge deck and the track deterioration process. Nevertheless, since the concepts are the same, the deterioration-based approach is analogous across applications. Hence, we focus more closely on demonstrating the approach and arriving at general conclusions at the conceptual level via the bridge deck case studies, rather than arriving at specific conclusions for Rapid Rail systems.

This approach provides us with explicit insight into the deterioration process, since models that comprise variables that have a direct influence on deterioration are used. For example, this method allows us to see the impact of a change in design on the deterioration evolution under certain situations. By comparison to the cost-based approach where we use real field data, with the deterioration-based model we are able to create hypothetical scenarios, based on a specific choice of inputs. Rather than using raw design, construction and condition data over time collected from facilities in operation, we use a mathematical model estimated using such data. Once this model is estimated, we can use it to compute the outcomes of hypothetical scenarios that are specified to put assess the sensitivities of interest. There are several dimensions that can be varied. For example, testing for the impact of changes in maintenance policy, changes in structural design or changes in traffic volumes. Each dimension has a set of values that it can take.

Thus, a scenario is defined by the values given to each of its dimensions. Using a specific experimental design, we introduce variability in the scenarios that we create. This allows for determining the differences in outcome that are caused by a difference in causal factors.

In this chapter, we first go through some background on bridge deck deterioration, before presenting the experimental design and its objectives. Then, we discuss the setup of the experiment for the application of interest, presenting the models, data and scenarios that are used. Finally, we present the implementation of the experiment, followed by the results and their interpretation in the light of the objectives of this study.

4.2 BACKGROUND ON HIGHWAY BRIDGE DECK DETERIORATION

The Bridge Deck deterioration process begins at the time of construction and ends at failure. Along the life span of concrete bridge decks, assuming no maintenance and no rehabilitation is performed, the parameters that influence deterioration can be grouped into four categories, namely bridge deck design, construction materials, construction techniques and environmental and usage factors (Carrier and Cady 1973). Within these groups, many factors contribute in determining the rate of concrete bridge deck deterioration.

4.2.1 BRIDGE DECK DESIGN

The rate of concrete bridge deck deterioration is affected by its design, namely superstructure type, structure type, thickness of concrete cover on steel reinforcing bars, span length, deck thickness, wearing surface type, grade of deck, and skew (angle of span with roadway). It has been shown that the superstructure type influences the rate of concrete bridge deck deterioration. For example, concrete bridge decks on steel superstructures deteriorate at a faster rate than concrete bridge decks on concrete superstructure, because the shrinkage between steel and concrete is different, hence leading to more spalls (Freyermuth et al. 1970, Carrier and Cady 1973).

Structure type also influences bridge deck deterioration. Simple span bridge deck structures usually have higher deterioration rates due to the flexibility of the simple span compared to the high stiffness associated with continuous concrete structures, for example (Wan Ibrahim, 1994).

The thickness of the concrete cover over the reinforcing steel bars also affects the deterioration rate of concrete bridge decks. Spalling, occurs generally due to deterioration of the reinforcing steel which separates the steel from the concrete. Spalling is usually a result of inadequate concrete cover over the reinforcing steel (Freyermuth et al. 1970, Carrier and Cady 1973).

Increasing span length also increases deterioration rates because the occurrence of transverse cracking is dependent on span length. Thickness of the concrete slab, type of protective system, effective drainage and skewness of the approach roadway are other design variables that affect concrete bridge deck deterioration.

4.2.2 CONSTRUCTION MATERIALS

Concrete is a composite material which consists of coarse aggregate embedded in a hard matrix of mortar – a mixture of cement and sand. The strength of the bridge deck is affected by the quality of the aggregate and of the mortar, namely shape, texture and size of the aggregate, water-cement ratio, type of cement, use of air-entraining agents for the mortar (Freyermuth et al., 1970).

4.2.3 CONSTRUCTION TECHNIQUES

Construction techniques that follow strictly the standard design specification will usually lead to the prevention of premature deterioration. As has been shown by Carrier and Cady (1973), contractors that adhere to the design specification construct more durable bridge decks. For example, observing proper curing and drying practices as well as minimizing the variations of air and water content throughout the deck will reduces its deterioration rate.

4.2.4 ENVIRONMENTAL AND USAGE FACTORS

Finally, the environmental factors that influence bridge deck deterioration are the presence of moisture (in the form of humidity and precipitation), temperature variations resulting in freeze-thaw cycles, and the traffic volumes.

4.3 EXPERIMENTAL DESIGN FRAMEWORK

In the previous section, we presented many different types of variables affecting deterioration of concrete bridge decks. Some of these influential variables are decided upon during the initial provision stage. So, knowing how deterioration is sensitive to these variables allows for better determining what values they need to be set to.

In this section we will discuss the experimental setup for the analysis. We present the objectives and the methodology through which we plan to achieve these objectives.

4.3.1 OBJECTIVES AND FRAMEWORK

As with the light rail case study, the main objective of this case study is to assess impact of initial conditions on the long-term performance of an infrastructure. However, initial condition and performance here are dealt with explicitly, unlike the light rail case. Under initial conditions, variables such as structure type and construction quality are considered. Since maintenance policy also plays an important role in the deterioration process, we take it into account to set the context in which the other variables interact.

In addition to assessing the sensitivity of long-term performance to initial conditions based on explicitly examining the deterioration process, this case study also demonstrates the validity and usefulness of the approach. The results need to be interpretable and the models well founded. Furthermore, the results should be presented in a way that can be translated into a cost analysis useful to decision-makers. In summary, determining and representing the sensitivity of deterioration to various factors, and demonstrating the validity and usefulness of this approach are the two major objectives of this case study.

The deterioration-based approach is built around the framework presented in Figure 8. The framework revolves around the deterioration process itself. We consider an input, which is a facility as initially provided, and the output of interest to us, namely the performance of the facility over its useful lifetime. The input is characterized by several variables that are the results of the decisions made during the early provision stages. Structure type, wearing surface, number of spans, construction quality and other design and construction considerations are determined initially and are constant throughout the life of the facility. These factors set initially potentially have an effect on the deterioration process. Since, part of the initial decision-making process is to determine the values that these variables take, knowing how initial factors influence the outcome is fundamental and motivates this study.

Furthermore, as indicated by Figure 8, there are other factors that influence the outcome. Throughout the life of the facility, there are temporal decisions that the agency can make to influence the outcome of interest through the deterioration process. This includes maintenance decisions for example. On the other hand, there are also uncontrollable temporal factors that affect the performance throughout the period of operation. This includes maintenance policy, for example. Traffic loads, weathering and natural catastrophes can be predicted to a certain extent, but vary without the decision-maker being able to control them.

So, in the light of the objectives of this case study, the focus is on how the outcome, namely the performance of the infrastructure over its lifetime, is affected by changes in the major influential factors. These influential factors are grouped into three categories, namely those that are set at initially provision, those that are decided upon throughout the lifetime and which affect the deterioration, and those which also are influential throughout the lifetime but cannot be controlled.

The following two sections focus on the methodology adopted to achieve the objectives of this analysis. To focus on the case study at hand, the variables relevant to bridge deck deterioration are presented and the models used to simulate the deterioration and maintenance processes are introduced.

4.3.2 VARIABLES

As shown in Figure 8, there are four major variable types that are of interest: initial condition variables, temporal decision variables, uncontrollable temporal factors, and output variables. Each is discussed in more detail in what follows.

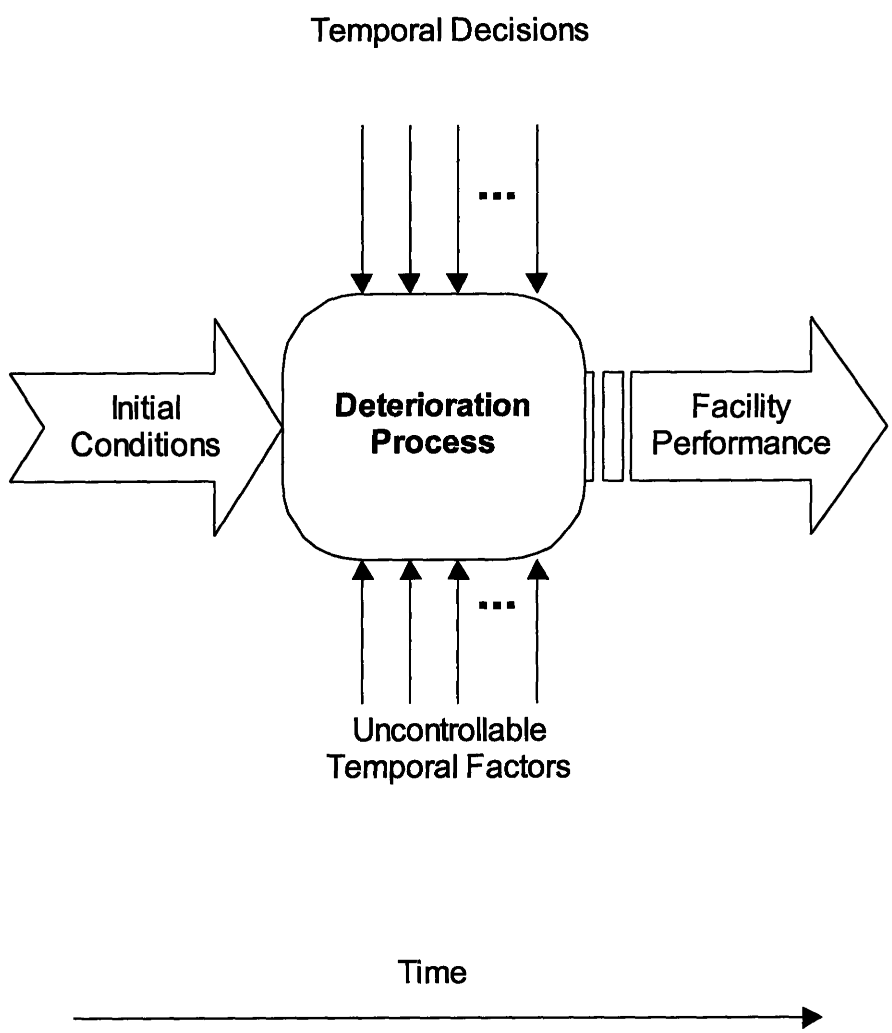


Figure 8: Conceptual Framework for Experimental Design

Initial condition Variables

The input to the deterioration process is the state of the infrastructure system when it is put in service. Initial condition is what we are concerned about. Our input is, therefore, the condition state of the infrastructure as it is delivered at the end of the construction phase. The initial condition is the result of the decisions made during the planning, design and construction phases. They thus include the following variables:

- Wearing surface type: the more resistant the wearing surface, the less the deterioration rate.
- Structure types: the higher the structural standards, the lower the deterioration rate. For example, using continuous or prestressed concrete span structure, or even both enhances the construction quality.
- Number of spans: the higher the number of spans, the more joints are used and consequently, the more prone the structure is to environmental factors, thus leading to possible higher rates of deterioration.
- Span length: the longer the spans, the greater the tension at its center, thus generating more stresses and deterioration.
- Skewness of main span with respect to the approach roadway: the greater the skew, the more lateral forces are added to the already existing forces in the alignment of the bridge, thus increasing further the stresses that the bridge deck is subjected to.

- Deck width: this variable matters because it influences the drying rate of the concrete, thus impacting the stress levels sustainable by the deck.

- Initial quality of construction: this variable plays a crucial role on the way the infrastructure deteriorates. As a matter of fact, initial quality of construction influences all other relationships, for it increases or decreases the strength of the relationships that bind the other factors to the deterioration process. For example, under a higher initial quality situation, the concrete will resist the stresses more effectively, thus weakening all stress-related deterioration relationships.

- Road type: interstate, primary or secondary

All these factors constitute the initial condition of the facility, the state at which it enters the deterioration process. As discussed in section 2.2, the initial performance level is dependent on these initial provision factors, and so is the deterioration rate. They will hence be one of the inputs to the deterioration model used to compute the outcome. But initial factors are not the only to influence the deterioration process. There are also uncontrollable factors that affect the facility throughout its lifetime.

Uncontrollable temporal Factors

There various uncontrollable factors that might influence the deterioration process include the following:

- Bridge Age

- ADT: Average Daily Traffic
- Climatic condition

These factors influence deterioration rates, while not being controllable. These are also factors whose impact on the deterioration is important. Especially interesting is the joint impact of controllable design and construction variables and uncontrollable factors. Therefore, the sensitivity of performance to controllable factors is assessed under different specific uncontrollable constraints.

The two categories of variables mentioned above are the ones influencing the deterioration process itself. They are used when modeling the deterioration of the facility. The initial condition of the facility affects both the initial and long-term performance of the facility, The uncontrollable factors, on the other hand influence the deterioration over the life of the facility.

Temporal Decisions

There are also decisions that affect the condition of the facility over its life. These decisions influence the way the condition of the facility evolves over time as well. Maintenance policy, for example, is a factor that will strongly influence the condition evolution. The choice of maintenance intensity and the regularity of the maintenance are decision-elements contributing to a satisfactory performance outcome. This is a factor that can be changed throughout the life of the facility.

Output

For the output to reflect the performance of the facility, we consider the condition state over time. Several points in time are considered to capture the evolution of the condition. As we will discuss in section 4.3.3, the output is characterized by a probability distribution of possible outcomes. Hence, the mean and variance of condition are the values of interest for our exercise, as a reflection of how well the system performs and how sensitive it is to input variables and other factors.

In the experimental setup, presented in section 4.4, we subject the system to the combined effect of deterioration and routine maintenance policy that does not vary over time (for simplification purposes) and does not include major rehabilitation. This along with the nature of the deterioration process may result in the system entering a steady state in the long run. Very naturally, we will consider this steady state as our long-term condition. Nevertheless, the rate at which this steady state condition is arrived at is also of interest. Therefore, several points in time assess the evolution of condition comprehensively.

In summary, this approach considers several design and operational variables that can be modified during the initial stages of the provision of a facility, and throughout its lifetime. Knowing how these factors influence the outcome is an important input to the decision making process that sets the values of these variables. The input variables and temporal factors are used in computing the condition outcome through models that are discussed in the subsequent section. We can then analyze the outcomes for different sets of values and thus determine the respective sensitivities.

4.3.3 DETERIORATION AND MAINTENANCE MODELS

This section introduces the modeling procedure followed to represent deterioration and maintenance activities. The deterioration process is modeled with inputs on the initial condition variables and the uncontrollable temporal factors. The maintenance policy is also modeled to represent the effects of the temporal decisions. The deterioration and maintenance models are then combined to compute the long-term performance of the facility as a probability distribution of condition states

Before introducing the models, we first present the condition measure adopted to assess bridge deck performance. This measure is in accordance with the Indiana Department of Transportation (INDOT) bridge deck condition data set that was used to estimate the models adopted in this study. The condition ratings used in the data set are specified by the Federal Highway Administration (FHWA, 1979) and are presented in Table 6 below. The ten (9 to 0, 9 being the best, 0 the worst) discrete infrastructure condition ratings or states used to assess a bridge deck condition are defined by a set of thresholds for operational adequacy and four other indicators measuring spalls, delaminations, electrical potentials and chloride contents.

Table 6: Concrete Bridge Deck Condition Ratings (FHWA 1979)

Condition Indicators (% Deck Area)

Rating	Spalls	Delaminations	Electrical Potentials	Chloride Content (lb/cu yd)
9	none	none	0	0
8	none	none	none > 0.35	none > 1.0
7	none	<2%	45% < 0.35	none > 2.0
6	<2% spall or sum of all deteriorated or contaminated deck concrete <20%			
5	<5% spall or sum of all deteriorated or contaminated deck concrete 20-40%			
4	>5% spall or sum of all deteriorated or contaminated deck concrete 40-60%			
3	>5% spall or sum of all deteriorated or contaminated deck concrete >60%			
2	Deck Structural capacity grossly inadequate			
1	Deck repairable by replacement only			
0	Holes in deck --danger of other sections of deck falling			

Furthermore, we chose to adopt a probabilistic representation of the deterioration process. Changes in condition over time are specified by transition probabilities, reflecting a more accurate representation of the probabilistic nature of infrastructure deterioration. The uncertainty of the prediction of condition states is due to unobserved explanatory variables, measurement errors, and the inherent stochasticity of the deterioration process.

We also adopt a discrete representation in time, namely the condition every second year, in accordance with the model and the FHWA guidelines. This, in addition to the discrete ratings and the probabilistic representation renders Markov chains appropriate and convenient to model deterioration. Markov chains are based on transition probabilities that translate the probability to move from a state i to a state j, given the condition at state i, in a given period of time. The reader is referred to Ross (1989) for greater detail on Markov chains. Transition matrices are used to gather all transition probabilities and are presented subsequently. This is all in consistency with the INDOT data set and the Markov chain model estimated using this data set.

Deterioration Matrices

The coefficients of the deterioration matrices are obtained through a deterioration model developed by S. Madanat, R. Mishalani and W. H. W. Ibrahim (1995). These transition probabilities are a function of variables that affect the deterioration process of a facility. These variables represent the initial condition and uncontrollable temporal factors presented in section 4.3.2 above.

In our bridge deck application, we have different deterioration models to predict the changes from one condition state to another, one for each departing condition state (Wan Ibrahim, 1994). They each have different explanatory variables. This allows us to differentiate among different stages of the deterioration process. For bridge decks, for example, deterioration is stress-induced in the early stages. But, as the facility deteriorates, a corrosion-induced deterioration contributes to a different type of decay, thus requiring a different deterioration model.

The different transition probabilities for each departing condition state are represented in a matrix. This square matrix represents all the probabilities of going from one condition state to another. The matrix is given by the following

$$\mathbf{P} = \begin{pmatrix} p_{kk} & p_{k(k-1)} & p_{k(k-2)} & . & \cdots & . & p_{k1} \\ 0 & p_{(k-1)(k-1)} & p_{(k-1)(k-2)} & . & \cdots & . & p_{(k-1)1} \\ . & . & . & . & \cdots & . & . \\ \cdots & \cdots & \cdots & . & \cdots & . & \cdots \\ . & . & . & . & \cdots & . & . \\ 0 & 0 & 0 & 0 & 0 & p_{22} & p_{21} \\ 0 & 0 & 0 & 0 & 0 & 0 & p_{11} \end{pmatrix} \quad (1)$$

where p_{ij} is the probability of going from state i to state j during the time period considered.

The Markov chain does not restrict the forecasted condition state into only one single value. Much rather, it models the probabilities of transition into various other condition states, thus capturing the uncertainty of the deterioration process. Furthermore, the probabilities are probabilities of moving to a state of lower condition only, for this matrix models only the deterioration process without any maintenance activity. Hence, the matrix is upper triangular. Since the matrix is computed based on deterioration models, it is naturally sensitive to the design variables, age, and other factors that influence the deterioration process.

A representation of the condition, consistent with the type of matrix discussed above, is the vector of probability mass distribution. This vector is composed of the various probabilities of being in a certain condition state. Such a vector is thus required for every period, for we need the probability mass distribution across condition states for every discrete observation point in time.

Through multiplication of the row vector representing the condition state distribution at the beginning of the period with the transition matrix, we thus obtain the condition state distribution at the end of the period, after the deterioration. This is presented in grater detail in section 4.4.2.

If C_{t-1} is the condition state column vector at period t-1, and P the transition matrix representing the deterioration process, then the condition state vector at time t is given by:

$$C_t^T = C_{t-1}^T \cdot P \qquad (2)$$

Maintenance Matrices

The same approach is applied to model the effects of maintenance on the condition of a facility. The matrix's coefficients represent the probabilities of moving from a given state to a higher condition state, based on the maintenance's effectiveness. The matrix will therefore be lower-triangular.

The joint-effect of deterioration and maintenance is captured by the matrix representing the product of the deterioration matrix with the maintenance matrix. If M represents the maintenance matrix, then the condition state vector at time t is given by:

$$C_t^T = C_{t-1}^T \cdot P \cdot M \qquad (3)$$

Through recurrent multiplications over time using equation (3), we obtain the condition state distribution for each time period. We can thus compute the long-term performance of a facility, as the probability mass distribution of the condition states that it will reach at the end of each period capturing the joint-effect of deterioration and maintenance.

In summary, in this chapter we presented the framework behind our experimental design. After listing and discussing the various variables that influence the deterioration process, we introduced the specifics of the model that we use to compute the outcome of interest, namely the long-term performance of a facility after yearly deterioration and maintenance cycles. These maintenance and deterioration cycles are modeled through Markov transition matrices computed based on the deterioration causal variables. As we will see in the following section presenting the experimental setup, these variables can be set to different values to create different scenarios. The analysis of the variation in outcomes for these scenarios will then allow us to determine the sensitivity of the performance of bridge decks to initial variables under different situations.

4.4 EXPERIMENTAL SETUP

In this section we are discussing the setup of the experiment. The objective is to put into application the framework developed in section 4.3.1 with the specification of the variables and methodology presented in sections 4.3.2 and 4.3.3. In what follows, we are first discussing the specification of the scenarios for the case study. Then, we explain how we compute the outcomes of these scenarios. This allows for the determination of the sensitivities and interpretation of the results in section 4.5.

4.4.1 SCENARIO SPECIFICATION

There are various variables that we can set during the experimental design. Each variable constitutes a dimension to the problem of assessing sensitivity to initial conditions. Since we are interested in the sensitivity of the outcome to initial conditions, we can vary each and every dimension, namely initial condition factors, uncontrollable temporal factors and temporal decisions. The variations can be individual or simultaneous. To create a set of observations with sufficient variability to allow for determining the sensitivities, we define different scenarios. Each scenario is defined by the values of its explanatory variables. We select a set of initial values for all variables to create a reference scenario. From there on, we vary the variables along all dimensions – initial condition, controllable and uncontrollable temporal factors – individually and simultaneously. In the analysis, the role of the scenarios is to test the sensitivities under varying situations, as reflected by the scenarios. The analysis of the outcomes of the different scenarios allows for detecting impacts of changes in variables, namely significance, direction and magnitude.

Figure 9 presents how each variable type impacts the deterioration process, as we defined it earlier in section 4.3.1. The rightmost column features the dimensions that we are varying when defining the scenarios. The center column presents the category to which the variables belong. The leftmost column features the elements the categories influence.

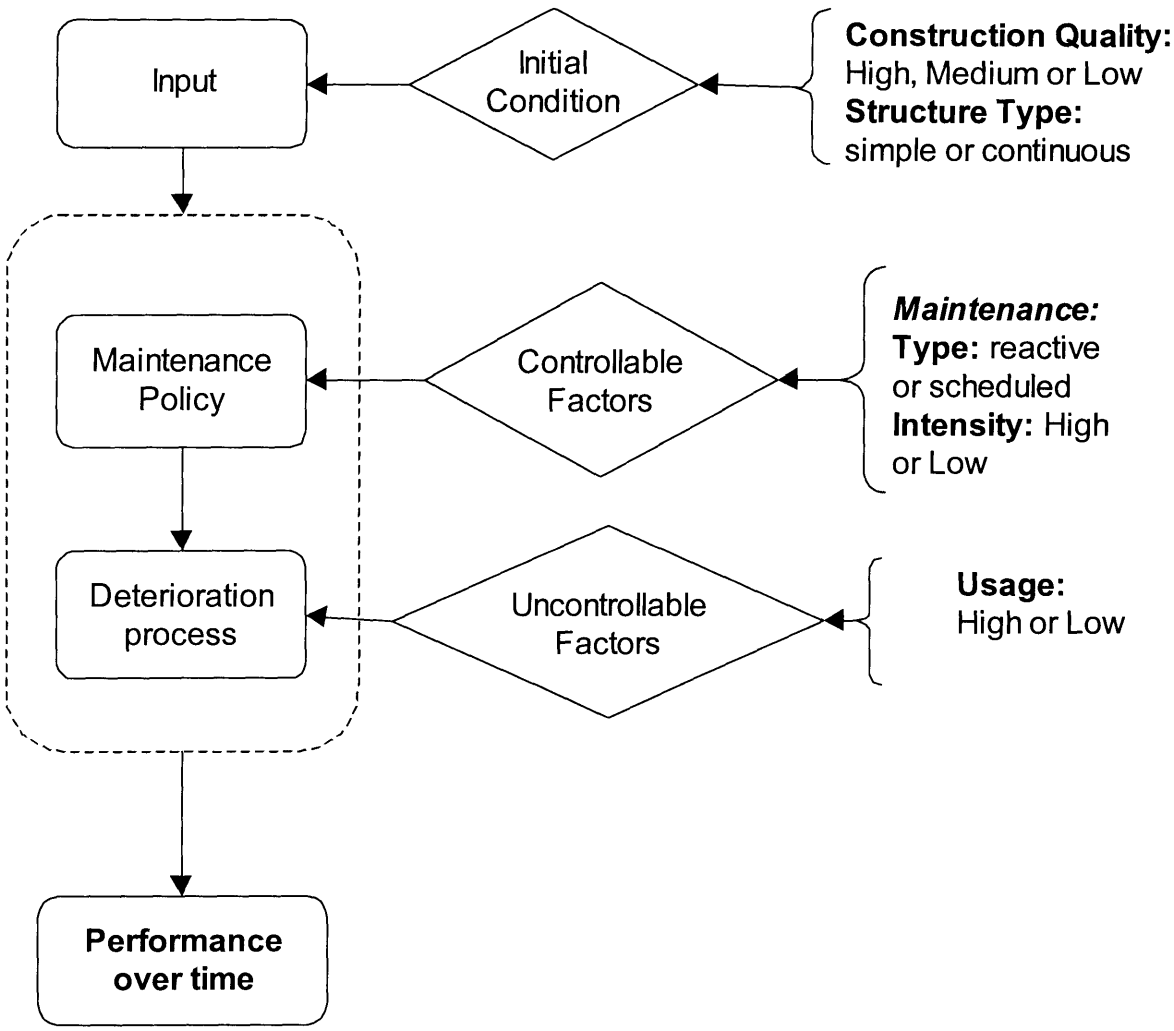


Figure 9: Type of variables and their effect on deterioration

As illustrated by Figure 9, we first have the choice of different initial conditions, by varying construction quality and structure type. We are also able to choose among different maintenance policies by changing the type (fixed schedule or reactive) and the intensity (low or high). Finally, uncontrollable temporal factors can also be varied by assigning different values to average daily traffic volumes.

Initial conditions and Uncontrollable temporal Factors

The different initial conditions reflect the quality level of the initial provision of the infrastructure and the design solutions than were adopted. In this case study, the definition of the condition states presented in Table 6 of section 4.3.2 restricts the representation of initial quality via the initial condition state. By definition of the condition states, all facilities irrespective of initial quality have to commence with condition state 9. The definition of the condition states does not allow for capturing initial quality effects through it. Therefore, the effects of initial provision quality are represented through alterations in the deterioration rates.

As discussed in section 4.3.3, deterioration models are used to compute the transition probabilities. These models feature the initial condition factors and the uncontrollable temporal factors. In this case study, we use three different initial qualities, namely high, medium and low. This alters the way the deterioration matrices are built. The matrix corresponding to the medium initial quality is built as described above. The transition probabilities are computed based on the deterioration model estimates by Wan Ibrahim (1994). However, the computation of the matrices corresponding to high and low initial qualities is slightly altered. To reproduce the effects of the quality on all the relationships, we respectively decrease or increase the deterioration model coefficients by 10%. This is equivalent to changing the rates of deterioration with respect to all its explanatory variables by 10%. We can then observe the effects of this 10% change on the outcome.

There are infinitely many possible scenarios to specify. For the sake of this case study, we chose to limit the number of different scenarios but still introduce sufficient variability to demonstrate the methodology and arrive at useful results. The two factors we decided to vary are structure type (initial condition factor) and Average Daily Traffic per lane (uncontrollable temporal factor).

The scenarios are thus built around the variations of these variables:

- Initial quality, which is either high, medium or low.
- Structure type, which is either simple concrete deck or continuous concrete deck.
- Average Daily Traffic per lane, which is either zero (no traffic) or 15,000 vehicles a day (high volume of traffic).

The other variables the deterioration model is based on are set at fixed values to limit the number of scenarios. They include the following:

- Wearing surface: type1, concrete without protective system (maximum deterioration)
- Climatic Region: North, where the freeze-thaw cycles take place, causing more deterioration
- Highway Class: secondary, they are designed to least resist deterioration

- Deck depth: 3 feet, which causes higher stresses than the average bridge deck
- Span Length: 80 feet, which also causes higher stresses than the average
- Number of Spans: 5, which also is a value generating higher than average deterioration
- Skewness: 0 degrees.

In all but the last case, we chose the values that are associated with higher than average deterioration. This way we are adopting scenarios that reflect serious deterioration concerns.

Now that all the factors have been set to a particular value in the different scenarios, we can compute the deterioration matrices associated with each scenario. As described before, the deterioration matrices are computed based on the characteristics of each scenario. Using the deterioration model developed by Madanat, Mishalani and Wan Ibrahim (1995), we calculate the deterioration transition matrix for every two year, for deterioration depends on age as well. Since we are considering a 50-year period, we thus have 25 matrices, one for every other year. The models introduced by Madanat et al only allow for the computation of transition probabilities up to condition state 3. States 2, 1 and 0 are never reached. This is because in the INDOT data set used for estimation, the occurrences of observation of bridges in condition states 2, 1 and 0 was too low to estimate a model. Therefore, for the purpose of this case study, these states are regrouped into one single state. This new state represents the state of maximum deterioration and represents the facilities in states 2, 1 and 0.

In summary, changes in initial conditions and in uncontrollable temporal factors allow for the creation of scenarios that result in different deterioration over time. For each scenario, we build the twenty-five corresponding deterioration matrices, one for every other year.

Maintenance Policies

Another influential factor is the maintenance policy put into effect. Building the scenarios, we have the choice of two characteristics to vary. First, maintenance intensity is an important factor determining the values that its transition probabilities take. The higher the maintenance intensity, the higher the increase in mean resulting condition state. This can be achieved by structuring the matrix in such a way that the outcome will be a higher condition state, allowing jumps of different magnitudes. Another way to influence the impact of maintenance is to change its scheduling. We could look at two possibilities when building the scenarios, namely maintenance at regular intervals or reactive maintenance. Maintenance at regular intervals is independent of the actual condition state. Reactive maintenance is associated directly with the condition states the infrastructure is in. During this maintenance policy, jumps in condition of a given magnitude are sought when the condition is observed to reach a certain level.

For this case study, a policy where maintenance at regular intervals is performed, is adopted. Bi-annual maintenance takes the following forms for each of two possibilities. For low maintenance intensity, the probability of ending up in the same condition state is 50%, of ending up one state higher is 25% and two states higher is 25% (for cases when 2-state transitions are possible). For high maintenance intensities, the probabilities are 25%, 25% and 50% respectively (for cases when 2-state transitions are possible).

Therefore, for high maintenance intensity, the maintenance matrix is as follows:

$$M_{high} = \begin{pmatrix} 1.0 & 0 & 0 & . & \cdots & . & 0 \\ 0.66 & 0.33 & 0 & . & \cdots & . & 0 \\ 0.50 & 0.25 & 0.25 & . & \cdots & . & . \\ \cdots & \cdots & \cdots & . & \cdots & . & \cdots \\ . & . & . & . & \cdots & . & . \\ 0 & 0 & 0 & 0.50 & 0.25 & 0.25 & 0 \\ 0 & 0 & 0 & 0 & 0.50 & 0.25 & 0.25 \end{pmatrix} \qquad (4)$$

For low maintenance intensity, the maintenance matrix is different and is as follows:

$$M_{low} = \begin{pmatrix} 1.0 & 0 & 0 & . & \cdots & . & 0 \\ 0.33 & 0.66 & 0 & . & \cdots & . & 0 \\ 0.25 & 0.25 & 0.50 & . & \cdots & . & . \\ \cdots & \cdots & \cdots & . & \cdots & . & \cdots \\ . & . & . & . & \cdots & . & . \\ 0 & 0 & 0 & 0.25 & 0.25 & 0.50 & 0 \\ 0 & 0 & 0 & 0 & 0.25 & 0.25 & 0.50 \end{pmatrix} \qquad (5)$$

These probabilities are independent of age and departing condition state, here. Although this assumption has its limitations, for the purposes of the primarily demonstrative nature of this study it is sufficient. More elaborate maintenance policy schemes can be tested as part of future research.

In this case study, we are only using the High and Low maintenance profiles. Since the most probable change in condition is shifted up by two condition states, we expect this to be reflected in the steady state distributions.

We thus have created 24 scenarios, based on variations of initial quality of provision (3 values), structure type (2 values), ADT/lane (2 values), and maintenance policy (2 values). A summary table of all scenarios with their outcomes is presented in Table 11 (page 123). The scenario are numbered as follows:

- A letter (a through H) to represent one of the 8 possible configurations of structure type, ADT/lane and maintenance policy.
- A qualifier (high, medium or low) to represent the initial quality of provision.

4.4.2 COMPUTING THE SCENARIO OUTCOMES

To conduct the sensitivity analysis, the outcome for each of the scenarios needs to be computed. Based on that, the sensitivities of the outcome to the various different inputs and factors can be analyzed. To do so, we analytically derive the outcome for each scenario based on the characteristics of the Markov chains.

Once we have the deterioration and maintenance matrices calculated, we can compute the outcome for each scenario. We recurrently compute the condition state distribution at every other year. This translates into two year increments. As presented in section 4.3.3, the probability mass distribution at year t given the probability mass distribution at year t-2 is given by:

$$C_t^T = C_{t-2}^T \cdot P_t \cdot M_{\text{int}} \qquad (6)$$

where,

$C_t{}^T$ = the transpose of the probability mass distribution vector at year t

C_{t-2}^T = the same vector at year t-2

P_t = deterioration transition matrix for the facility at age t

M_{int} = the maintenance matrix, where it represents the intensity required by the scenario under examination.

The equation above only computes the changes in condition states for one cycle. This process thus needs to be repeated recurrently to compute the probability mass distribution of condition states for every year. Hence, the probability mass distribution vector at time t can be written as a function of the probability mass distribution vector at time zero as follows

$$C_t^T = C_0^T \cdot \prod_{k=1}^{t/2} \left(P_{2k} \cdot M \right) \qquad (7)$$

The recurrent multiplications by the deterioration and maintenance matrices reproduce the deterioration and maintenance processes for every cycle. The condition state evolves from year to year, submitted to degradation (through the deterioration matrix of that particular year) and to maintenance (through the maintenance matrix). We thus obtain the Probability Mass Distribution in the form of one vector for every other year for each scenario.

4.5 RESULTS AND INTERPRETATIONS

4.5.1 INTRODUCTION

The sensitivity analysis is performed based on the results of computing condition state outcomes for each scenario. This will take the form of comparing the outcomes and how they change when the factors change. Holding one factor constant, we compare the different condition states resulting from the combinations of the other values. To analyze the sensitivity of the outcomes to initial construction and design standards, we examine the results at two levels of aggregation. The first one is based on the mean condition state. This provides an assessment of the sensitivity of average condition. The second level examines further the details of the outcomes by considering the probability distributions of the condition states.

At the distribution level, one can see early signs of sensitivity that are worth focusing on. To look at the different scenarios, we plot their Probability Mass Distributions. There are two sets of plots. The first one features the same base scenario with all three possible initial qualities. The other set depicts the distributions at age 10, 20 and 50 for a given scenario.

The first set of eight plots helps us understand the impact of Initial Construction Quality on the facility. Even if we cannot quantify the sensitivity, we are able to qualitatively assess the direction of interaction and the relative significance and amplitude of the sensitivity in comparison with other scenarios. For example, the more "fanned out" the distributions are, the higher the sensitivity. On the other hand, the more concurrent the distributions, the less sensitivity there appears to be. The second set of plots represents the 24 scenarios separately. For each scenario, the distributions at year 10, 20 and 50 are shown. This set of graphs helps us assess the rate at which the steady state is reached, as explained and interpreted in section 4.5.2. The more the distributions are spaced apart, the less rapidly the facility deteriorates, thus the less rapidly the steady state is reached.

This analysis will provide us with some interesting insights into the sensitivities that exist, and their relative importance. Nevertheless, it needs to be complemented by a quantification which can be achieved through the analysis of the mean outcomes and standard deviations.

In analyzing the different outcomes that we get from the different scenarios, one way to compare them is to compute the mean condition state and variance for each one of them. The mean condition state is calculated by summing the product of the value of the condition state with the probability of being in that state as follows:

$$\bar{s} = \sum_{s=1}^{9} s \times P_s \qquad (8)$$

where, P_s is the probability to be in state c at the time considered.
Similarly, the variance is given by:

$$Var(s) = \sum_{s=1}^{9} \left(s - \bar{s}\right)^2 \times P_s \qquad (9)$$

Once both mean and standard deviation have been calculated for each scenario, we can use them as a basis of comparison.

The next step is to choose the factor whose impact on sensitivity is to be analyzed. Let us, for the sake of an example, choose the structure type factor. We thus have twelve scenarios with structure type 1 (simple concrete) and twelve with structure type 2 (continuous concrete). The way we constructed the scenarios allows us to pair them up, so that each pair is identical, except for the structure type (same ADTL, same initial quality, same maintenance intensity). For each pair, one can calculate how the change in structure type reflects in a change in the mean outcome and standard deviation. The sensitivity can be expressed in percentage change as follows:

$$Sensitivity = \frac{\bar{s}(Structure \quad Type \quad 1) - \bar{s}(Structure \quad Type \quad 2)}{\bar{s}(Structure \quad Type \quad 1)} \qquad (10)$$

where $\bar{s}(\cdot)$ = mean across a structure type.

This method allows us to compare sensitivities. It also allows for defining common thresholds above which the sensitivities are considered significant. The thresholds can be common since we are normalizing them to percentages.

One has the alternative of either analyzing the twelve pairs separately, or of averaging out all the differences in mean, to calculate an average sensitivity to the change in a particular factor. While the first method provides a more detailed understanding, the second method offers a more aggregate understanding. It is reminded that the results presented in thus section are illustrative of the methods chosen. They should not be considered conclusive for they are aimed at demonstrating the methodology and revealing its potential in producing certain types of results.

4.5.2 ANALYSIS AT THE DISTRIBUTION LEVEL

Impact of Initial quality

Initial quality clearly has an impact on the outcome. This is expected to be the case since the scenarios are designed such that the deterioration matrix varies with initial quality. Nevertheless, the impact is quite uneven, depending on the scenarios that we are looking at. A first look at charts 1 through 8 confirms that cases with higher Initial quality have higher probability of ending up in a higher condition state, and lower probability of ending up in a lower condition state. This is clearly only reflecting the model and scenario specification that we adopted. The charts a figured at the end of this chapter, starting page 130.

However, a closer look reveals the following interactions. Sensitivity to initial quality is greater when maintenance is at a higher standard. This reflects in plots that are almost overlapping for Low Maintenance intensity, while they are significantly more shifted for High Maintenance, as can be seen by comparing charts 1 with 2, 3 with 4, 5 with 6, and 7 with 8. Furthermore, traffic also impacts the sensitivity quite importantly. The more traffic, the closer the plots, as can be seen by comparing charts 1 with 3, 2 with 4, 5 with 7, and 6 with 8. Hence, the more traffic there is, the less sensitive the facilities are to Initial quality. Finally, structure type does not seem to have any significant impact on the sensitivity to Initial quality. Charts 1 with 5, 2 with 6, 3 with 7, and 4 with 8 look very similar, and the relative spacing remains the same for different traffic levels.

Considering the interaction between initial quality and maintenance intensity, we can provide the following interpretation. Higher maintenance greatly increases the sensitivity to initial quality. When a facility is subjected to a low maintenance policy, it deteriorates at a faster rate. This deterioration seems to reduce the differences that exist between facilities with different initial qualities. On the other hand, high maintenance reduces deterioration and exacerbates the differences, rendering them more apparent. In other words, the worse the maintenance policy chosen, the less the initial provision standard matters.

With regard to traffic, the reasoning is quite similar. The higher the traffic, the more deterioration there is. Thus, the less difference there is between different initial qualities. In other words, the more a bridge has to support traffic, the less it matters whether it has low or high initial quality. When looking at these two scenarios, one has to keep in mind that the design for a bridge that supports a lot of traffic is quite different from a design for a bridge that supports only little traffic.

With respect to the type of structure, however, the interactions are quite different. The structure type does not seem to influence the sensitivity to initial quality significantly. It appears that, everything else being equal, facilities of the two structure types are almost equally sensitive to changes in initial provision standard. Hence, when considering which Initial quality to choose, one does not need to be concerned about the type of structure of the different scenarios under consideration. This analysis only considers the simple and continuous structure types. This is a consequence of the deterioration models used to compute the deterioration matrices. These models only differentiate simple concrete structure type from the three others, namely continuous concrete , simple prestressed and continuous prestressed. Hence the models really consider simple concrete structure on one hand, and all other structure type on the other.

Facilities are sensitive to Initial quality. Nevertheless, the sensitivity appears to be quite different depending on the other influential factors. High maintenance and low traffic are examples of factors that foster stronger sensitivity to Initial Quality.

Impact of Maintenance Intensity

Maintenance intensity also has a definite impact on the Probability Distributions. First, as expected, the most probable state shifts from condition state 4 to condition state 6, when high maintenance is applied, as can be seen when comparing charts 1 with 2, 3 with 4, 5 with 6 and 7 with 8. This is in accordance with the way we modeled maintenance intensity. Since we favored a jump of two condition states for high maintenance, whereas we had zero for low maintenance, we did expect this to be reflected in the distributions.

Second, low maintenance seems to accelerate deterioration. In other words, the lower the maintenance standards, the more rapidly the facility reaches its steady state, as explained below. Steady state is discussed more comprehensively later on in this section. For the purposes of this discussion it suffices to say that the steady state condition is the condition state a facility may settle in the very long-term. The result implies that infrastructure performs better than its steady state for a shorter period of time. Thus, when a high maintenance policy is applied, not only does it result in a better steady state, but also the rate at which this steady state is reached is slower, which means that the facility performs better than the steady state for a longer period of time. This result can e seen when comparing charts 9 with 10, 11 with 12, 13 with 14, etc. Finally, as mentioned before, better maintenance increases the impact of initial quality of provision.

So, maintenance plays a great role in determining the deterioration profile. It impacts the steady state (mean condition as well as distribution) and the rate at which this state is reached. Maintenance also changes the impact of other variables, such as initial quality, whose sensitivities are different depending on the maintenance policy in place.

Impact of Other Factors

Average Daily Traffic per lane (ADT/lane) is another factor that influences the outcome directly. The direct impact of higher traffic volume is increased deterioration, i.e. the distributions shift towards the lower condition states. Though this is not very apparent for low maintenance cases, it becomes highly visible for high maintenance cases, as can be seen by comparing charts 1 with 3 (low maintenance), 2 with 4 (high maintenance), 5 with 7 (low maintenance) and 6 with 8 (high maintenance). This comes as expected and reflects how traffic impacts were modeled. Bridge decks are more sensitive to traffic when they are subjected to high maintenance policies.

Another factor to influence performance is the type of structure. The sensitivity to structure type seems very limited. Not perceptible for low maintenance cases, it is hardly visible for high maintenance cases. Hence, structure type does not seem to be that important a variable, for scenarios are only sensitive to it to a very limited extent.

Reaching the Steady state

After a certain period of time, the facility can reach a steady state. When it is in a steady state, the maintenance and deterioration balance each other out during each time period. Consequently, the distribution of condition states remains exactly the same for each period, once the steady state is reached. Let us first derive the Steady state analytically.

The theorem on the existence of limiting probabilities (Theorem 4.1 in Ross (1989)) states that for an irreducible ergodic Markov chain, limiting probabilities exist and are independent of the condition state and are given by:

$$\pi_j = \lim_{n\to\infty}\left(K^n\right)_{ij} \qquad (11)$$

$$\sum_{j=0}^{9}\pi_j = 1 \qquad (12)$$

$$\pi_j = \sum_{i=0}^{9}\pi_i \cdot K_{ij} \qquad (13)$$

where,

π_i = limiting probability for state i

K_{ij} = element of the matrix resulting from the product of the deterioration matrix with the maintenance matrix.

$(K^n)_{ij}$ = element of the matrix resulting of n products of the matrix K defined above.

Equation 11 is a definition of the limiting probabilities. Equation 12 is the normalizing equation because all probabilities need to add up to 1. Equation 13 translates the definition of limiting probabilities in mathematical language, namely the limiting probabilities remain unchanged when submitted to another deterioration and maintenance cycle. The system has reached its steady state. Equation 12 and 13 form a network of 11 solved to compute the π's.

Though the theorem assumes a constant transition matrix, it still applies in this case study because the deterioration matrices become age dependent after a certain period of time. We can thus use the product of the deterioration matrix at year 50, which is assumed to have reached the state of age independence, with the maintenance matrix to form the matrix K used in equation 13.

The theorem provides a convenient way to calculate the steady state from the product of the deterioration and maintenance matrices. In all cases, the Probability Distribution obtained by this method, with the matrices corresponding to year 50, matches the distribution obtained through recurrent multiplication to compute the probability mass distribution at year 50, as determined by equation 6 in section 4.4.2 (to within 4 significant digits). Nevertheless, we rely on the recurrent multiplication method to obtain intermediary results for years earlier than 50. This verification confirms the existence of the steady state by year 50.

Though one important aspect of the sensitivity is the differences in outcome that exist between various design and construction configurations and standards, sensitivity is not only of interest with respect to specific points in time and the steady state of each scenario. The rate at which this steady state is arrived at also matters, for it reflects the intensity of the. This aspect is observable when plotting the Probability Mass Distributions at age 10, 20 and 50. What follows is purely a result of the analysis using Markov models and should not be viewed as general conclusions. At age 10, the facility has suffered initial deterioration only, and is still very young. At age 20, however, the facility is much closer to the steady state or slowly transitioning into it. At age 50, the steady state is reached in all cases. This is the state where deterioration and maintenance balance each other out exactly, during each time period.

Let us consider what influences the time that it takes to arrive at the steady state, as an indicator of what influences the intensity of the true degradation that is taking place. To support this, we will refer to charts 9 through 32.

First, initial quality influences the rate of convergence to the steady state. The better the quality, the slower the process, as pictured in charts 9,13 with 17, 10,14 with 18, 11,15 with 19, etc. In other words, the facility stays in a better condition longer. There is a double effect here because, not only does the facility end up in a better state, but it takes longer to come down to this lower state from the highest condition state. So, overall, the facility performs better, and for a longer period of time. It is reminded that assumed maintenance policies do not include major rehabilitation. Thus, at no point in time is the facility restored to its initial condition.

Second, maintenance intensity affects the rate significantly. In the high maintenance cases (charts 9, 11, 13, 15, etc.), the facility takes significantly more time to reach the Steady state, than it does in the corresponding low maintenance cases (charts 10, 12, 14, 16, etc.). Here again, the same double effect takes place where the facility performs better and for a longer period of time.

Traffic increases the deterioration, thus the rate at which the facility converges to its steady state. Hence, a facility which supports a high ADT/lane will arrive at its Steady state more rapidly, as can be seen in charts 9 with 11, 10 with 12, 13 with 15, 14 with 16, 17 with 19,etc.

Finally, factors like structure type have ambiguous effects. As a matter of fact, the nature of convergence is only very marginally sensitive to structure type. Also it appears that the effect can go in either direction: slowing down, or speeding up the process. But since the effect does not seem to be significant, we cannot really trust the direction of these effects.

In summary, the analysis at the distribution level allows us to acquire a detailed insight into the deterioration process and its sensitivity to various factors. The qualitative results that are gathered from this analysis set the stage for the quantitative analysis conducted at the aggregate level. There we will look deeper into the effect of maintenance on the outcome and its influence on the role of other factors. We will also address the question about the sensitivity to Initial quality. Finally, we will look into design issues via Structure type, and usage via Average Daily Traffic per lane (ADT/lane).

4.5.3 ANALYSIS AT THE AGGREGATE LEVEL

Now that we have a better knowledge of the qualitative aspects of sensitivity, we explore ways to express it quantitatively next. The methodology used to examine the mean outcomes is presented in section 4.5.1 above. The average sensitivities are computed as the average of the individual sensitivities. This allows for a good approximation of the sensitivity of certain groups of scenarios, and allows for comparisons between groups.

Impact of Initial quality

As discussed in section 4.4.1, we introduce a 10% change in the coefficients of the deterioration models used to compute the deterioration transition matrices. This allows for modeling changes in initial quality. The effect of that change on the results is assessed by analyzing the resulting change in the mean condition state outcome. These changes are presented in Table 7. The first four columns identify the scenarios and their characteristics. The base case that we compare to is medium initial quality. The two rightmost columns represent the resulting changes in mean condition state at year 50 as measured by percent changes from the base computed as discussed in section 4.5.1.

				% Changes in condition due to	
ADT/L	Maint.	Structure	Scen. ID	Low Initial Quality	High Initial Quality
0	low	cont.	E	-1.03%	1.37%
0	high	cont.	F	-3.09%	3.74%
15K	low	cont.	G	-0.70%	0.93%
15K	high	cont.	H	-1.51%	2.00%
0	low	simple	A	-0.94%	1.25%
0	high	simple	B	-2.72%	3.40%
15K	low	simple	C	-0.67%	0.89%
15K	high	simple	D	-1.37%	1.81%
			Average	**-1.58%**	**2.02%**

Table 7: Sensitivities at year 50 to changes in Initial quality

The first observation is that the average sensitivities to Initial quality are quite low: 1.57% on average for a 10 % increase in deterioration rates, and an increase of 2.01% for a 10 % decrease in deterioration rates (reflecting an improvement in initial quality). It is reminded here that the 10% change in quality is not a change in initial quality *per se* but a change in the rates of deterioration. The investigation of the relationship between the two is very important but not within the scope of this thesis. Therefore, it is reserved for future research.

Nevertheless, we notice clear patterns in the sensitivities to Initial quality. For instance, the sensitivities are higher for cases of high maintenance by an average of 1.32% with respect to changes under low maintenance for an increase in deterioration rates (lower initial quality), and by an average of 1.61% with respect to changes under low maintenance for a decrease in deterioration rates (higher initial quality). The same analysis for ADT/lane shows that sensitivities to changes in initial quality of provision in cases of high traffic are lower by 0.86% and 1.02% respectively, with respect to changes under no traffic.

Furthermore, by examining joint-effects, the sensitivities of cases with high maintenance and low traffic are higher than those of high maintenance and high traffic. They are also higher than those of low maintenance and low traffic. In addition, they are significantly higher than those of low maintenance and high traffic.

With regard to the Structure type variable, very small differences in sensitivity exist. They are -0.16% on average when comparing cases of continuous structure type to cases of simple structure type. However, this value is so small compared to the others (5 to 10 times less), that we can confidently state that Structure type does not affect the sensitivity of condition to Initial quality.

The conclusions here are analogous to those based on the distributions, except that we now quantified the impacts of the various factors. We can thus confirm the previous observations based on the distribution-level analysis. High Maintenance and Low Traffic both increase the sensitivity of the outcome to Initial quality, whereas Structure type has very limited impact.

The same analysis can be performed to assess the sensitivity to changes in maintenance intensity. From the results presented in Table 8, we gather that the average sensitivity of mean condition state at year 50 to the change in maintenance intensity from low to high is quite substantial. When applying a high maintenance policy, the long-term outcome is, on average, 22.4% higher than that of low maintenance policies.

Here also, we can see certain patterns. An obvious one is the change in sensitivity with Initial quality. A higher Initial quality fosters more sensitivity to maintenance practices. This means that, the better the initial provision standard for the facility, the more it is sensitive to the maintenance policy. In other words, if a high standard of initial provision is adopted, implementing a high maintenance policy brings comparatively better results than if a low standard of initial provision had been chosen.

Another visible difference is between scenarios that support different traffic volumes. Scenarios of zero traffic are, on average, 6.35% more sensitive to changes in maintenance policy than scenarios with 15,000 vehicles per day. Here again, the changes in sensitivity due to Structure type changes are minimal: 1.25% on average, which is negligible, compared to the other changes.

Ini Q	ADT/L	Structure	Scen ID	% change in condition due to high maintenance	avg.
Low	Low	Cont	E	24.1%	
Med	Low	Cont	E	26.7%	26.8%
High	Low	Cont	E	29.7%	
Low	High	Cont	G	18.3%	
Med	High	Cont	G	19.3%	19.4%
High	High	Cont	G	20.5%	
Low	Low	Simple	A	22.3%	
Med	Low	Simple	A	24.5%	24.6%
High	Low	Simple	A	27.1%	
Low	High	Simple	C	18.1%	
Med	High	Simple	C	18.9%	19.0%
High	High	Simple	C	20.0%	
			Average	**22.4%**	

Table 8: Sensitivities at year 50 to changes in Maintenance Policy

For changes in Average Daily Traffic per lane, from zero to 15,000 vehicles, the average change in mean condition state outcome at year 50 is a decrease of 3.60%, as indicated by *Table 9*. This figure is quite low, considering the fact that we are comparing the "No Traffic" cases with cases sustaining high volumes of vehicles (15,000 a day per lane, for a secondary road). The resulting interpretation of this figure is that traffic matters only slightly in bridge deck deterioration, for there is only a small difference between the two extreme usage cases. A closer examination reveals that scenarios with high maintenance policies are somewhat more sensitive to changes in traffic volumes, and so are scenarios with higher initial standards of provision. On the other hand, low maintenance cases do not exhibit significant sensitivity. Nevertheless, even the numbers for specific scenarios are relatively small to warrant conclusion that traffic matters significantly in influencing long-term performance of bridge decks.

With regard to changes in structure type, we can see in Table 10 that the impact is almost negligible. Changing from a simple to a continuous concrete structure does not provide any apparent benefits from a long-term deterioration point of view. The choice of structure type may be important when designing the deck to support certain loads, but it does not have a significant effect on the long-term performance of the deck. Here also, high maintenance and low traffic yield different results, but they are all still low.

Table 9: Sensitivities at year 50 to changes in Traffic

Ini Q	Maint	Structure	Scen ID	% change in condition due to 15K ADT/L	avg.
Low	Low	Cont	E	-0.85%	
Med	Low	Cont	E	-1.17%	-1.21%
High	Low	Cont	E	-1.60%	
Low	High	Cont	F	-5.45%	
Med	High	Cont	F	-6.97%	-6.98%
High	High	Cont	F	-8.52%	
Low	Low	Simple	A	-0.68%	
Med	Low	Simple	A	-0.95%	-0.98%
High	Low	Simple	A	-1.30%	
Low	High	Simple	B	-4.09%	
Med	High	Simple	B	-5.41%	-5.46%
High	High	Simple	B	-6.87%	
			Average	**-3.65%**	

Table 10: Sensitivities at year 50 to changes in Structure type

Ini Q	Maint	ADT/L	Scen ID	% change in condition due to continuous structure	avg.
Low	Low	0	A	-0.22%	
Med	Low	0	A	-0.30%	-0.31%
High	Low	0	A	-0.42%	
Low	High	0	B	-1.67%	
Med	High	0	B	-2.04%	-2.02%
High	High	0	B	-2.36%	
Low	Low	15K	C	-0.05%	
Med	Low	15K	C	-0.08%	-0.08%
High	Low	15K	C	-0.12%	
Low	High	15K	D	-0.26%	
Med	High	15K	D	-0.40%	-0.41%
High	High	15K	D	-0.59%	
			Average	**-0.71%**	

Table 11 summarizes all the scenarios and their respective outcomes. It also introduces the standard deviation and coefficient of variation (standard deviation over mean) observed for each distribution. The coefficient of variation (COV) reflects the certainty around the predicted mean outcome. The greater the COV, the lower the certainty, for there is more variation around the mean.

Table 11 shows some differences in standard deviations. High maintenance invariably causes an increase in the variance and to a lesser extent in the Coefficient of Variation. Hence, even if high maintenance increases the mean condition state outcome, it also increases to some extent the uncertainty of the outcome, as predicted by the deterioration model.

High ADT/lane, on the other hand, causes the scenarios with different initial quality of provision to look more alike (i.e. less differences in variances). Hence, high traffic increases the certainty of the predictions of outcome made through the model.

Table 11: Summary Statistics of all Scenarios

Scenario	A-Low	A-Med	A-High	B-Low	B-Med	B-High	C-Low	C-Med	C-High	D-Low	D-Med	D-High
ID	**1**	**9**	**17**	**5**	**13**	**21**	**3**	**11**	**19**	**7**	**15**	**23**
Ini Q	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Maint	Low	Low	Low	High	High	High	Low	Low	Low	High	High	High
ADTL	0	0	0	0	0	0	15K	15K	15K	15K	15K	15K
Struct.	Simple	Simple	Simple	Simple	Simple	Simple	Simple	Simple	Simple	Simple	Simple	Simple
Mean	5.20	5.25	5.31	6.36	6.53	6.76	5.16	5.20	5.25	6.10	6.18	6.29
Std Dev	1.12	1.20	1.31	1.64	1.86	2.11	1.04	1.09	1.15	1.20	1.30	1.42
CV	0.22	0.23	0.25	0.26	0.29	0.31	0.20	0.21	0.22	0.20	0.21	0.23

Scenario	E-Low	E-Med	E-High	F-Low	F-Med	F-High	G-Low	G-Med	G-High	G-Low	G-Med	G-High
ID	**2**	**10**	**18**	**6**	**14**	**22**	**4**	**12**	**20**	**8**	**16**	**24**
Ini Q	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Maint	Low	Low	Low	High	High	High	Low	Low	Low	High	High	High
ADTL	0	0	0	0	0	0	15K	15K	15K	15K	15K	15K
Struct.	Cont	Cont	Cont	Cont	Cont	Cont	Cont	Cont	Cont	Cont	Cont	Cont
Mean	5.21	5.27	5.34	6.46	6.67	6.92	5.17	5.20	5.25	6.11	6.21	6.33
Std Dev	1.15	1.25	1.38	1.87	2.12	2.37	1.04	1.09	1.16	1.24	1.34	1.49
CV	0.22	0.24	0.26	0.29	0.32	0.34	0.20	0.21	0.22	0.20	0.22	0.24

A scenario is defined by a letter (representing a combination of Maintenance, ADT/L, and Structure Type) and Initial Quality (low, medium, high)

4.6 SYNTHESIS

The deterioration-based approach yielded some interesting results, in terms of both demonstrating a methodology to test the sensitivity of deterioration and long-term performance to initial conditions, and understanding the role of certain variables in the deterioration process. Though there were some limitations to this approach, it also has benefits that allow for a more in depth analysis the cost-based approach of chapter 3 does not allow for. In what follows we present the benefits in terms of methodology in general and the bridge deck deterioration case study. Subsequently, the limitations of the deterioration-based approach are discussed as well.

4.6.1 BENEFITS OF THE DETERIORATION-BASED APPROACH

Pursuing the deterioration-based approach complemented the cost-based approach in various ways. We were able to demonstrate the value of this methodology which can be applied to various types of facilities, in assessing infrastructure performance sensitivity to initial provision standards. We also learned more about the deterioration process and the variables affecting it, by focusing on bridge deck deterioration. Though the application of our analysis to bridge decks is not comprehensive by any means, some interesting findings are worth summarizing. In what follows, we first summarize the methodology-related findings, before summarizing those related to bridge deck deterioration. Since this case study was limited in scope, the results should only be viewed as illustrative of the value of the methodology rather than providing final conclusions on the sensitivities of performance to initial conditions.

First, unlike the cost-based approach, which represented a very broad and indirect perspective on deterioration with many assumptions and approximations of the variables of interest, this approach focuses explicitly (and in more detail) on the deterioration process itself.

Since we actually model the deterioration process, we can specify the scenarios of interest, which is a great advantage. Even though the results are dependent on the validity of the deterioration model used, the use of explicit variables rather than proxies reinforces the confidence that we have in the approach and findings.

There are also various possible interactions between the variables of interest. We consider the effect of an explanatory variable on the outcome. We can also consider the effect that a variable has on the impact that another variable has on the outcome. For instance, the sensitivity to a certain variable can be defined directly as the average impact of the change in that explanatory variable given the values that other variables are at. It can also be defined as the impact that a change in that variable has on the sensitivity of another variable. The effect of maintenance intensity on the sensitivity of performance to initial quality is an example of that.

Indeed, from the bridge deck case study it is observed that the more severe the deterioration is, the less sensitive long-term infrastructure performance is to initial conditions. The facilities that are the least deteriorated are the ones that are the most sensitive to changes in initial condition or temporal factors such as Average Daily Traffic per lane. Good condition seems to intensify the strength of the relationships that exist between variables. The better the state the facility is in, the more its performance is sensitive to changes in its explanatory variables. For example, it appears that the facility which is performing better, namely the one subjected to high maintenance intensity, is more sensitive to changes in traffic volumes.

Another important result is that long-term performance of bridge decks is slightly sensitive to initial quality of provision. We saw that a 10% in the deterioration rates resulting in a 1% to 3% change in the condition state outcome of the deterioration process. Moreover, the more deterioration is limited via the choice of certain variables such as maintenance intensity, the better the facility will react to higher standards of provision. The same is true about maintenance policies. The better the initial quality of provision, the better the facility reacts to higher maintenance intensities.

On the other hand, performance seems to be less sensitive to variables like usage, than it is to variables such as maintenance intensity and initial quality of provision. The same can be said about structure type, which does not seem to influence deterioration at all.

Therefore, the value of the deterioration-based approach is clear. Moreover, a deterioration-based analysis can be built up to the cost-level through the use of appropriate cost models. As discussed in chapter 6, this allows for the decision-makers to work at the economic level, similarly to what the cost-based approach attempts to do.

4.6.2 LIMITATIONS OF THE DETERIORATION-BASED APPROACH

It is important to emphasize that in this case study we examined high deterioration scenarios. In specifying the scenarios, we varied the four variables initial quality, maintenance intensity, Average Daily Traffic per lane and structure type, while setting all the others (including wearing surface, climatic region, highway class, deck depth, span length, number of spans and skewness) at values expected to result in relatively higher deterioration. This clearly restricts the range of possible results that can be realized. Therefore, the results should be considered with the scope of the study in mind. If we take the example of the "Structure type" variable, it might well be that if less deterioration takes place, the facility indeed be sensitive to changes in type of concrete structure. On the other hand, limiting the case study to the examination of a few scenarios allows for a more in depth analysis that focuses on the primary issues of interest.

Furthermore, the manner in which maintenance activities are modeled leaves room for improvement during future research. The model used in this study assumes constant effectiveness across all condition states and, more importantly, across all scenarios. Age, traffic, climate and structure type are variables that potentially influence maintenance effectiveness. This would require modeling maintenance effectiveness, as a function of these and other design and construction variables. Moreover, our assumption of equality of effectiveness across condition states might be too strong. Let us consider the hypothetical example of a road that has two regions with cracks of different sizes. If these two regions are subjected to the same maintenance activity, the effect of maintenance is conceivably less for the region with the wider cracks. Hence, a different maintenance effectiveness is required for each region. Furthermore, we restricted the maintenance policy to the same actions being applied every year, and for all condition states. It would also be interesting to pursue an approach where the policy is allowed to change over the years and is a function of the condition state. These suggestions, however, are out of the scope of this study and should be addressed in future research.

Finally, some of the specified scenarios may not be considered as very common. For instance, maybe a multiple span, simple concrete deck with no protectant on the wearing surface might not be a common configuration for bridges that support 15,000 vehicles per day per lane.

However, it is certainly possible with the appropriate data and information to check into the plausibility of the scenarios. For the purpose of this study where the demonstration of the methodology is the primary objective, such specific scenario confirmations are not of the prime concern.

Having laid down some of the limitations of this case study, it is important to point out that these limitations are not particularly inherent to the deterioration-based methodology. They are primarily limitations in the scope of its application to bridge decks and, therefore, can be overcome via a more elaborate experimental set up and analysis. For the purposes of this case study, the scope is confined to meet the objective of demonstrating the approach rather than arriving at final and comprehensive conclusions.

Chart 1: Scenarios A

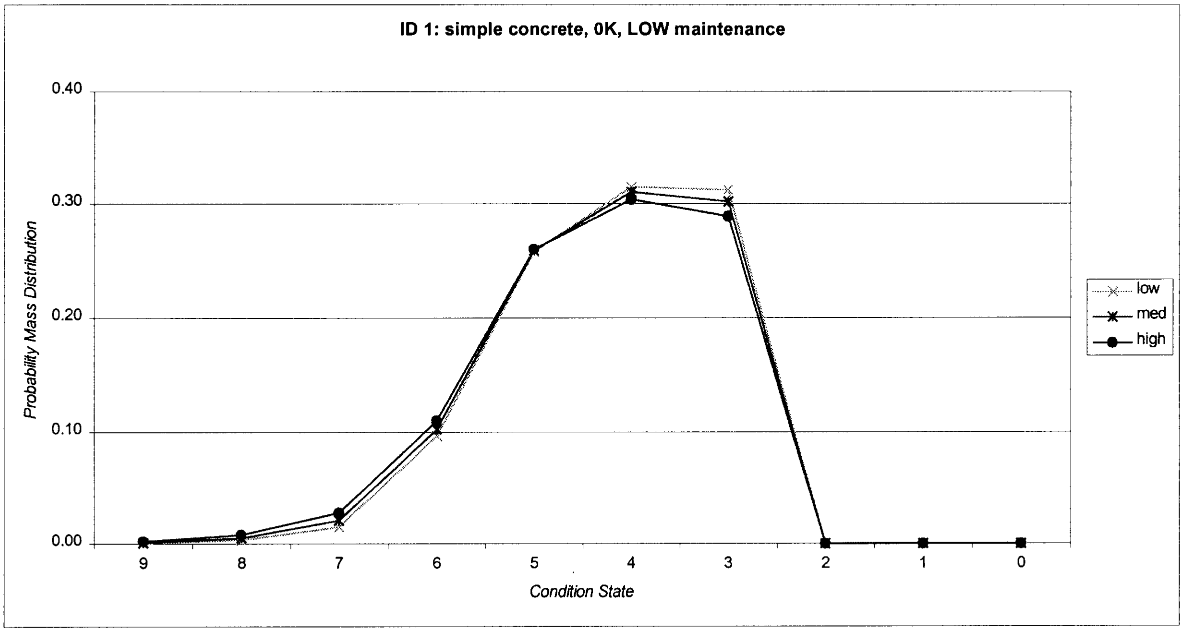


Chart 2: Scenarios B

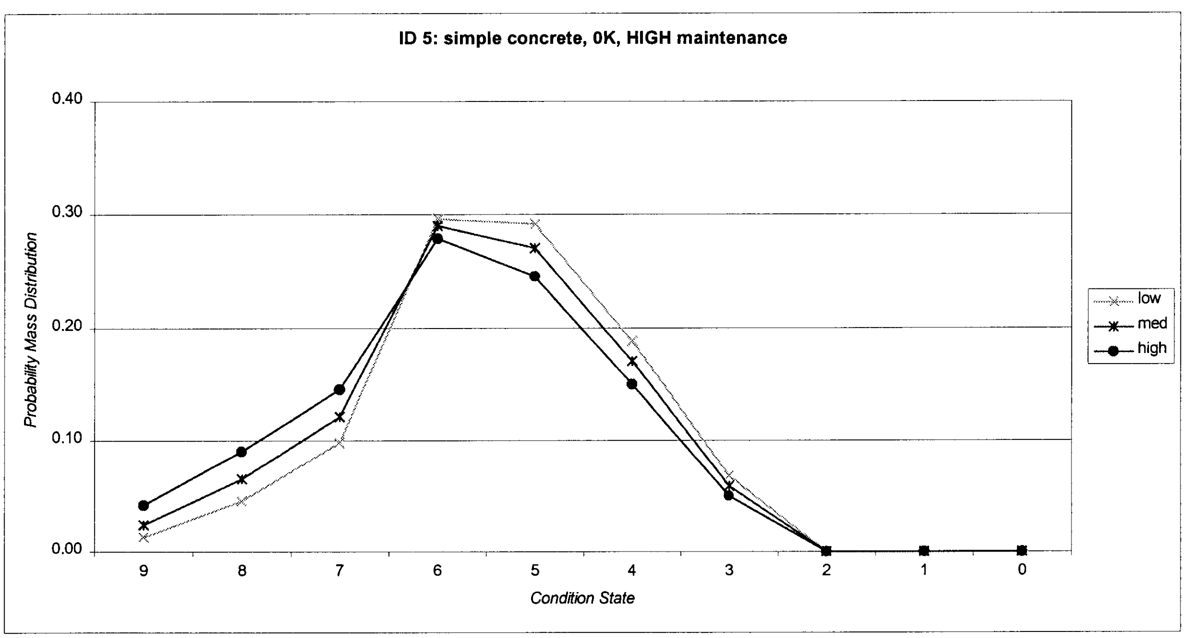


Chart 3: Scenarios C

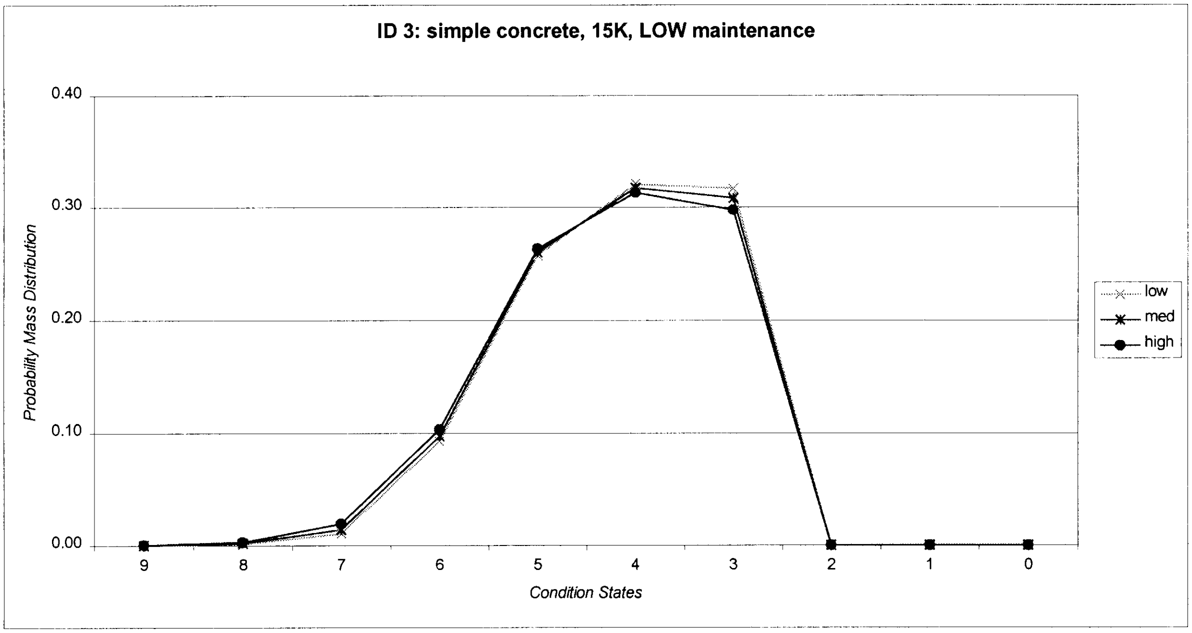


Chart 4: Scenarios D

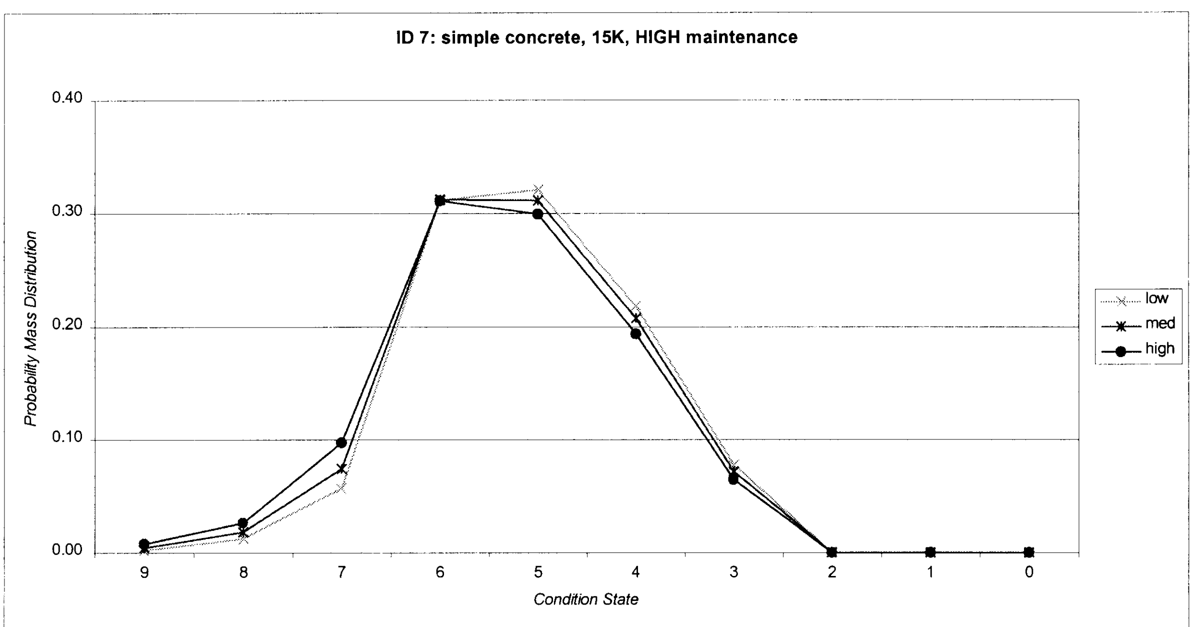


Chart 5: Scenarios E

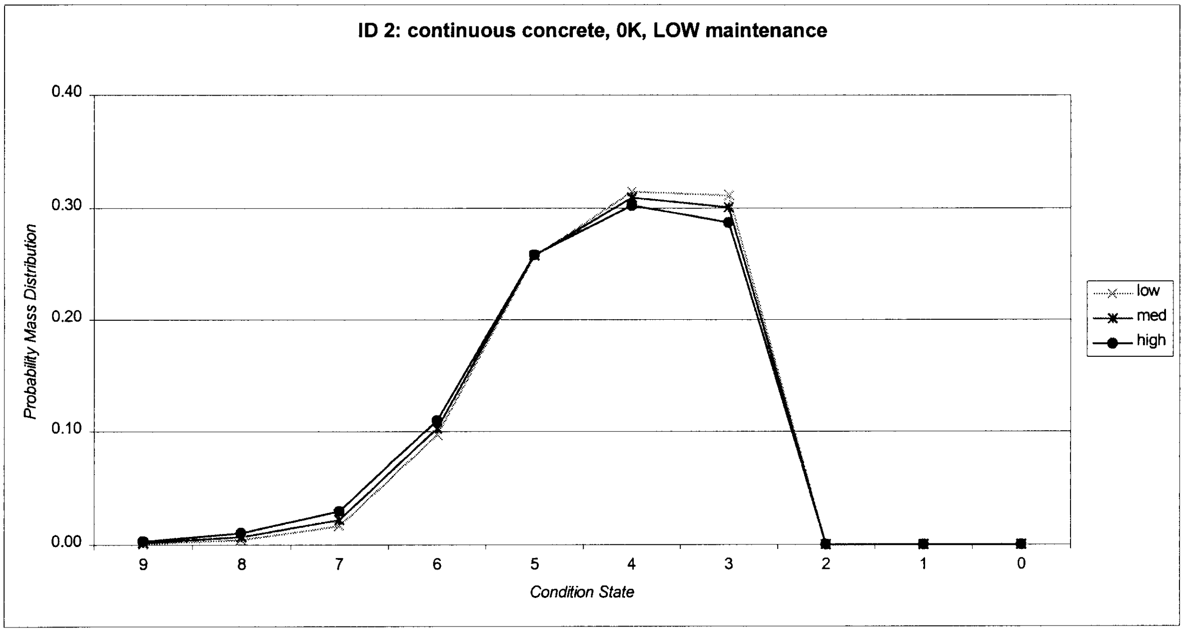


Chart 6: Scenarios F

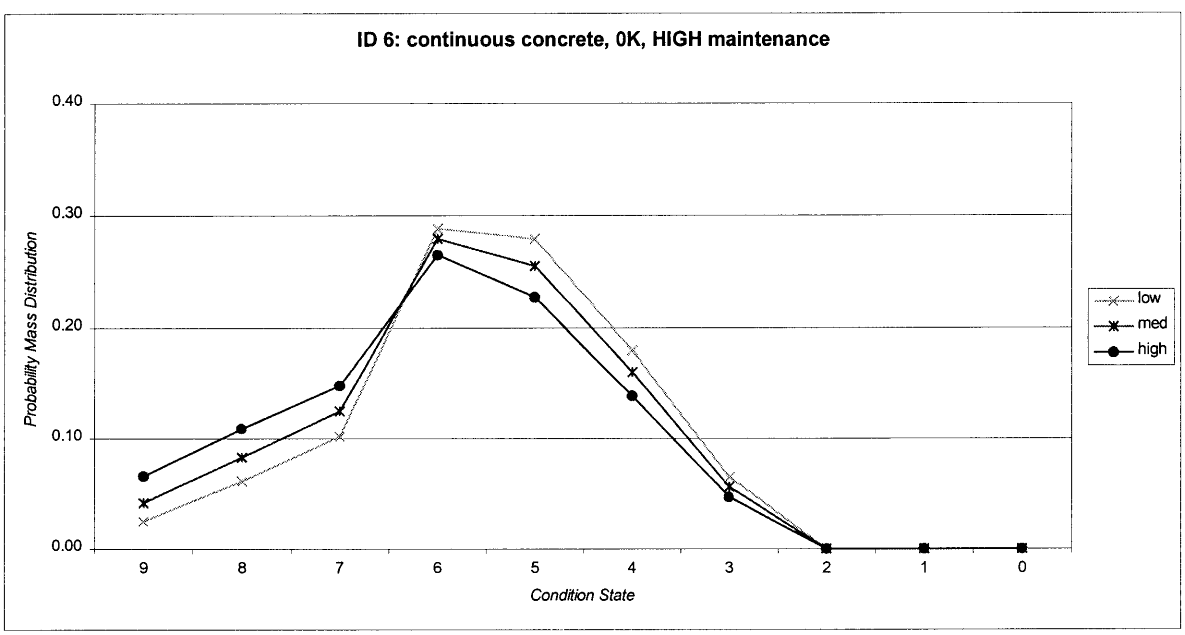


Chart 7: Scenarios G

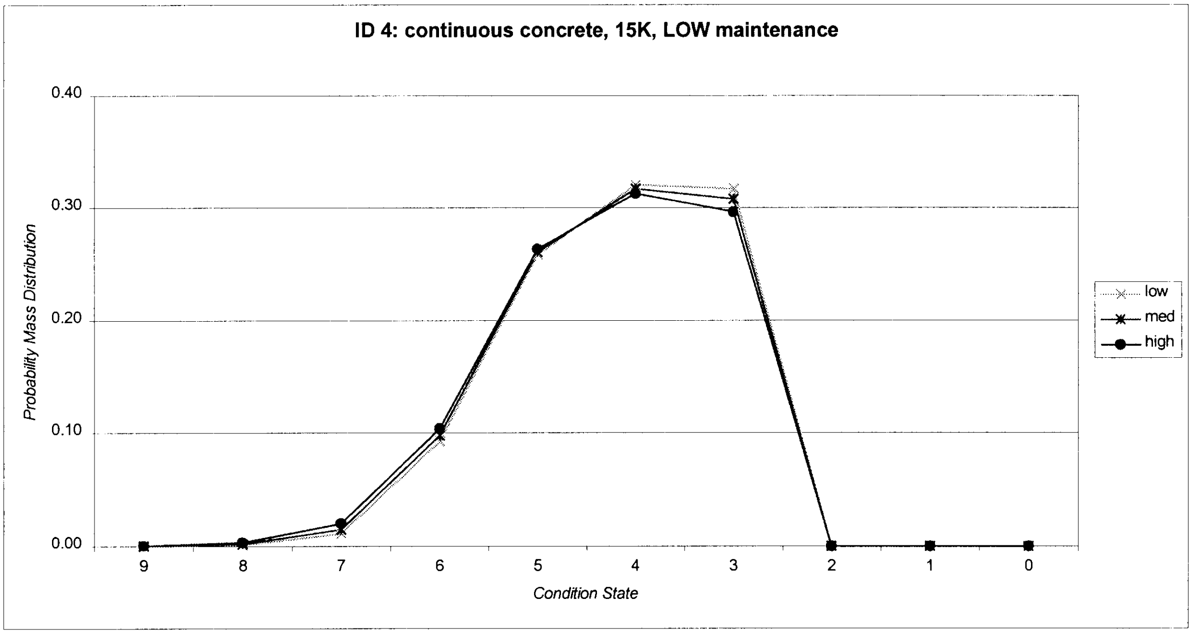


Chart 8: Scenarios H

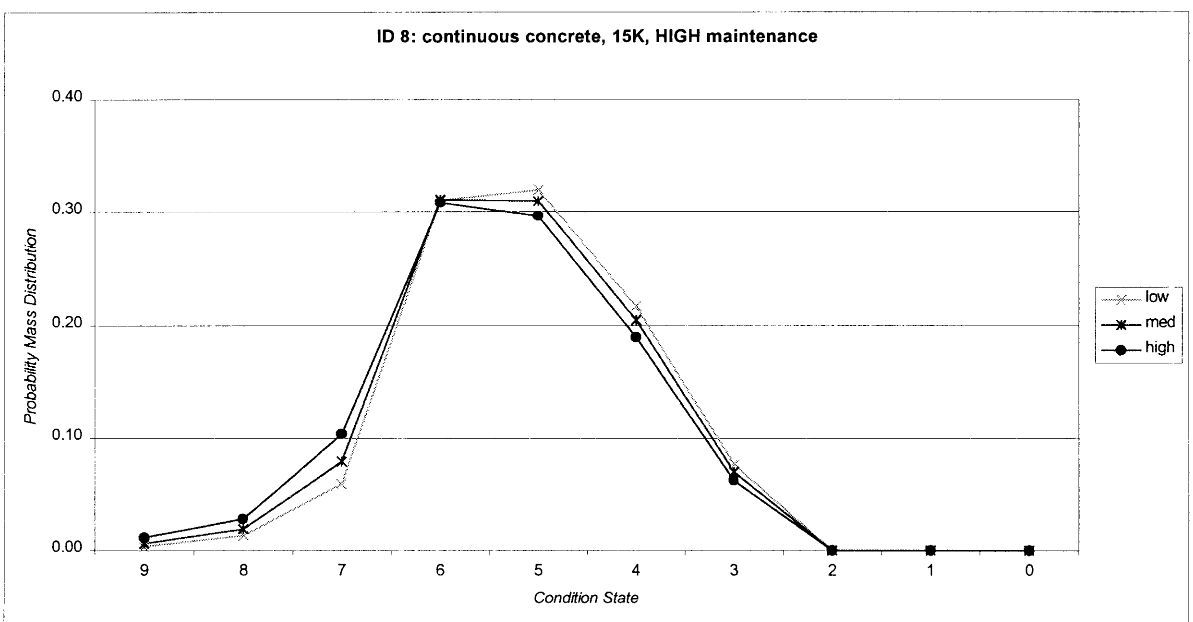


Chart 9: Scenario A (Low Quality)

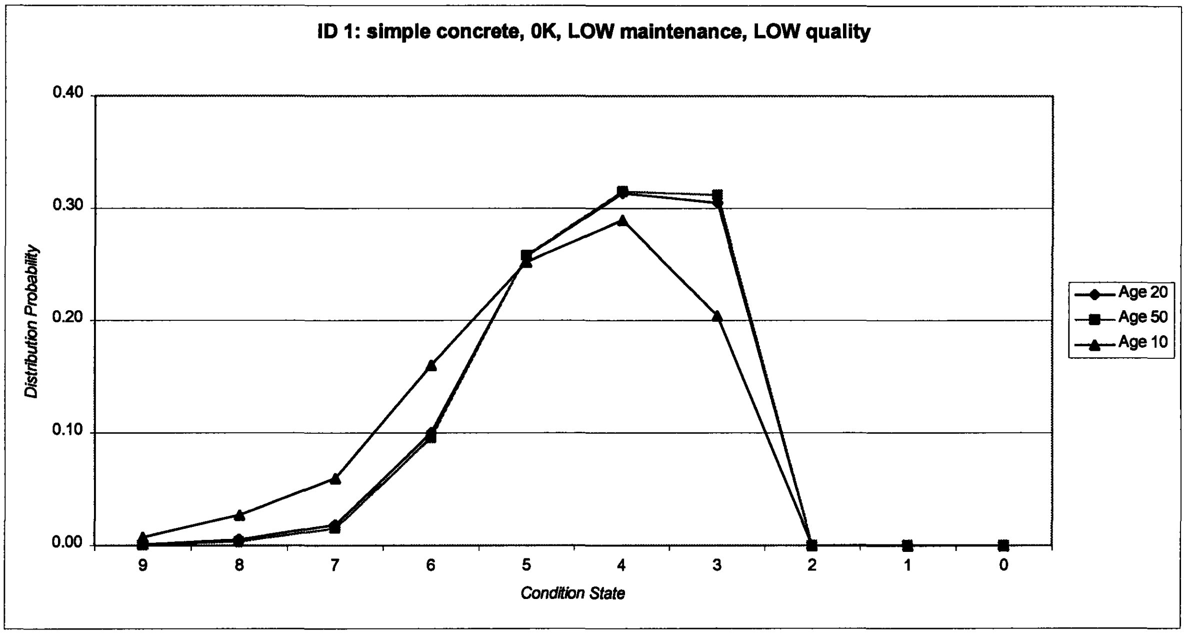


Chart 10: Scenario B (Low Quality)

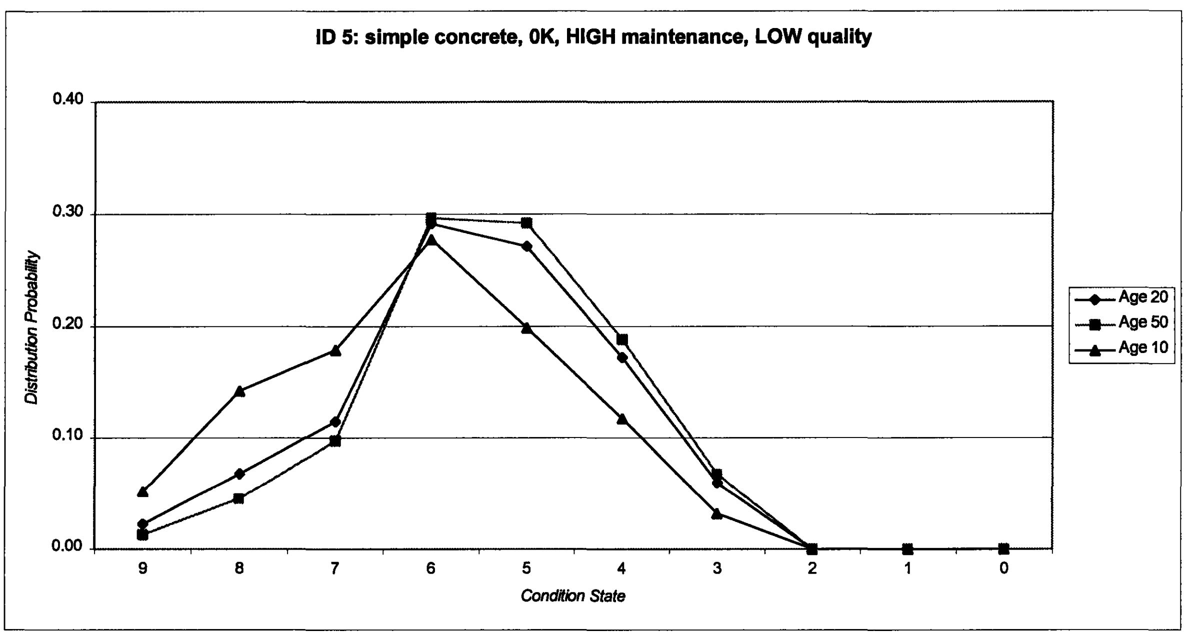


Chart 11: Scenario C (Low Quality)

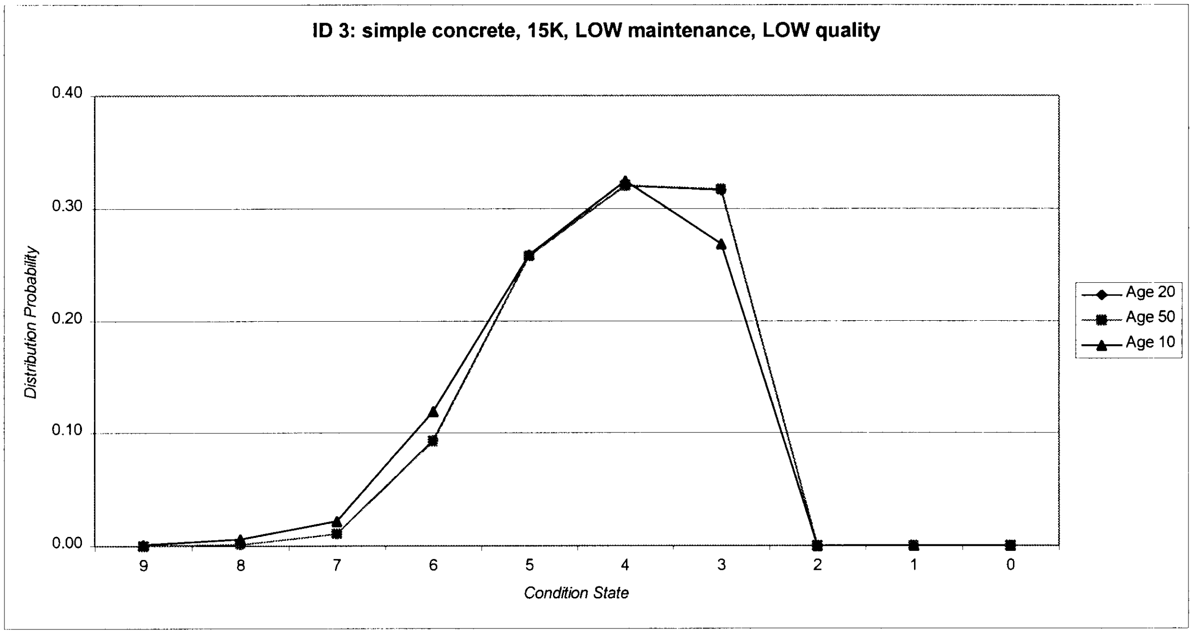


Chart 12: Scenario D (Low Quality)

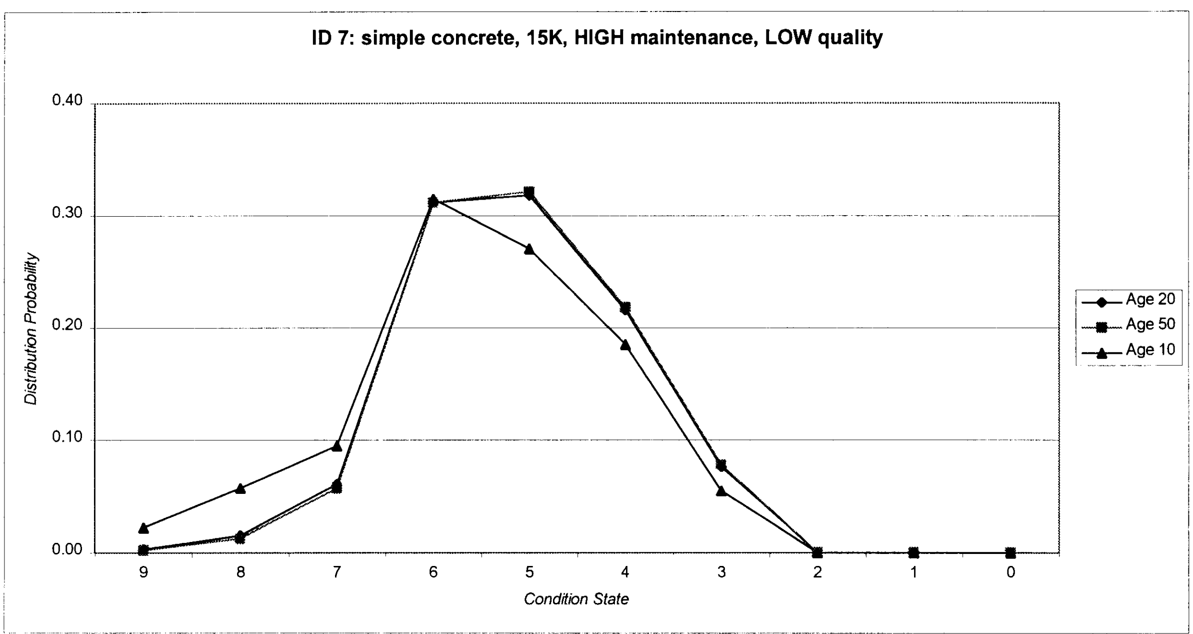


Chart 13: Scenario A (Med Quality)

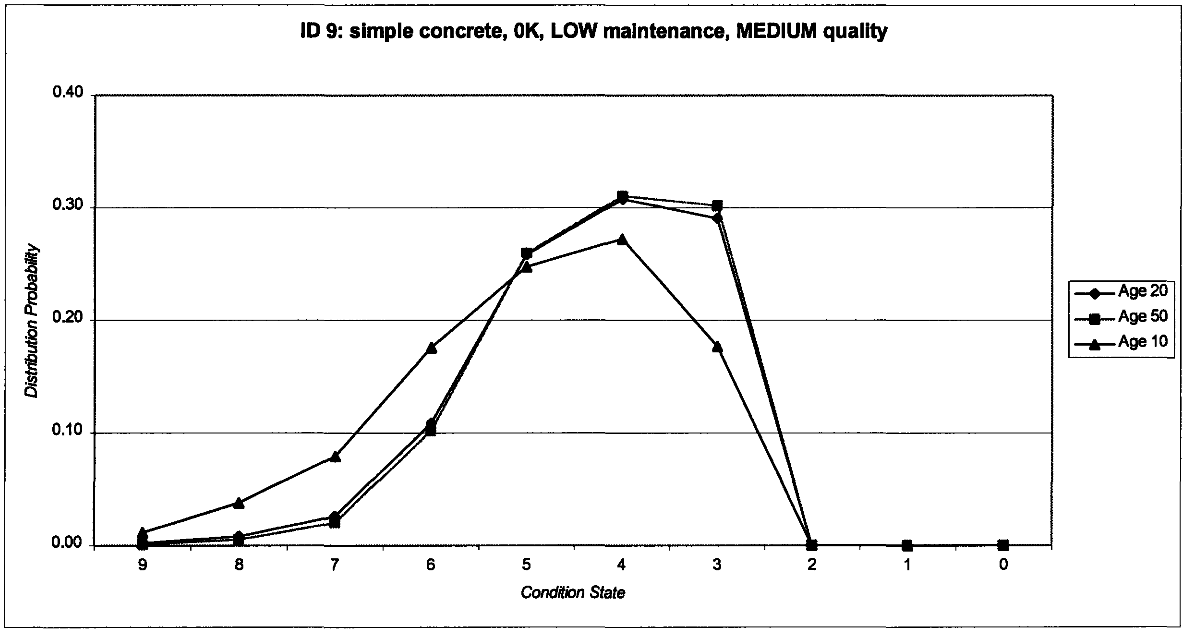


Chart 14: Scenario B (Med Quality)

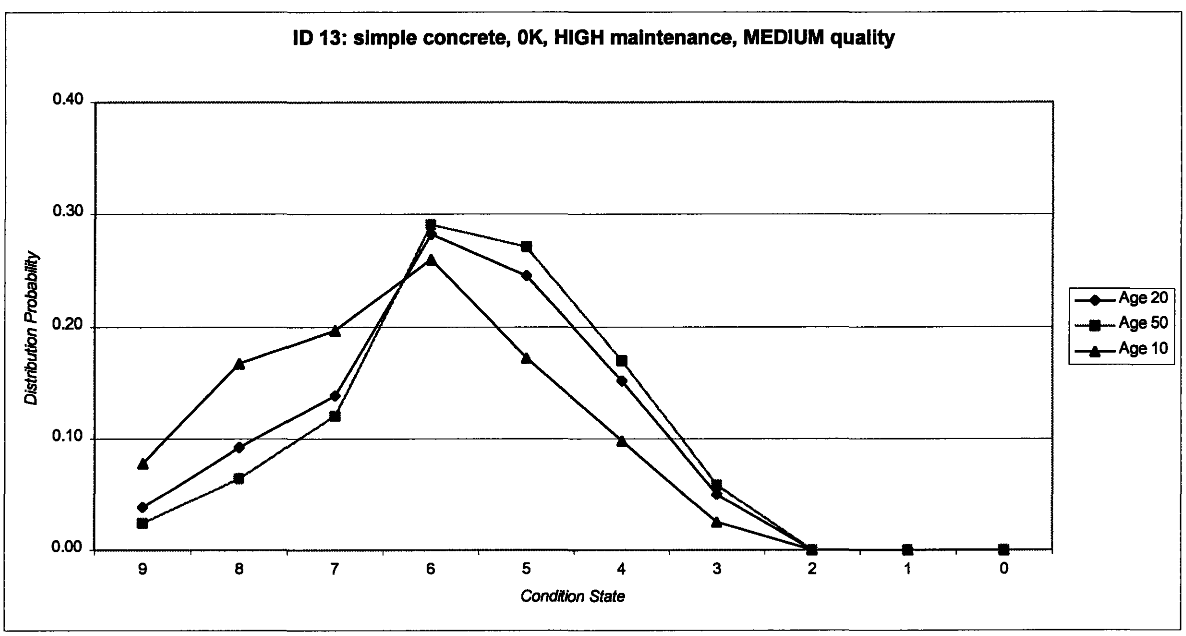


Chart 15: Scenario C (Med Quality)

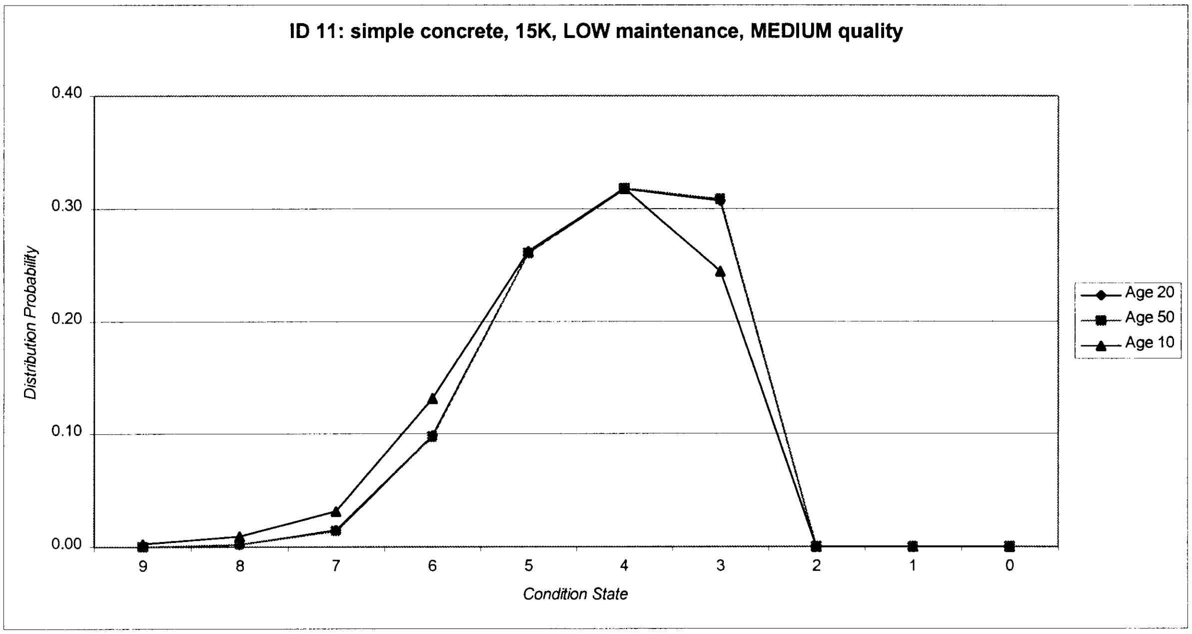


Chart 16: Scenario D (Med Quality)

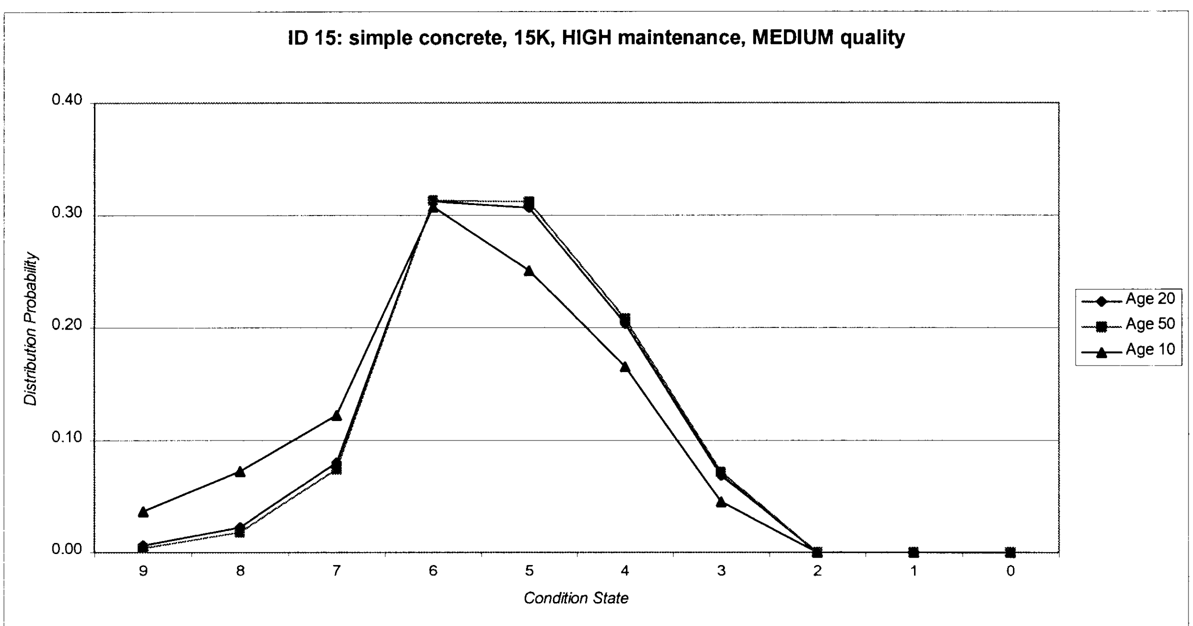


Chart 17: Scenario A (High Quality)

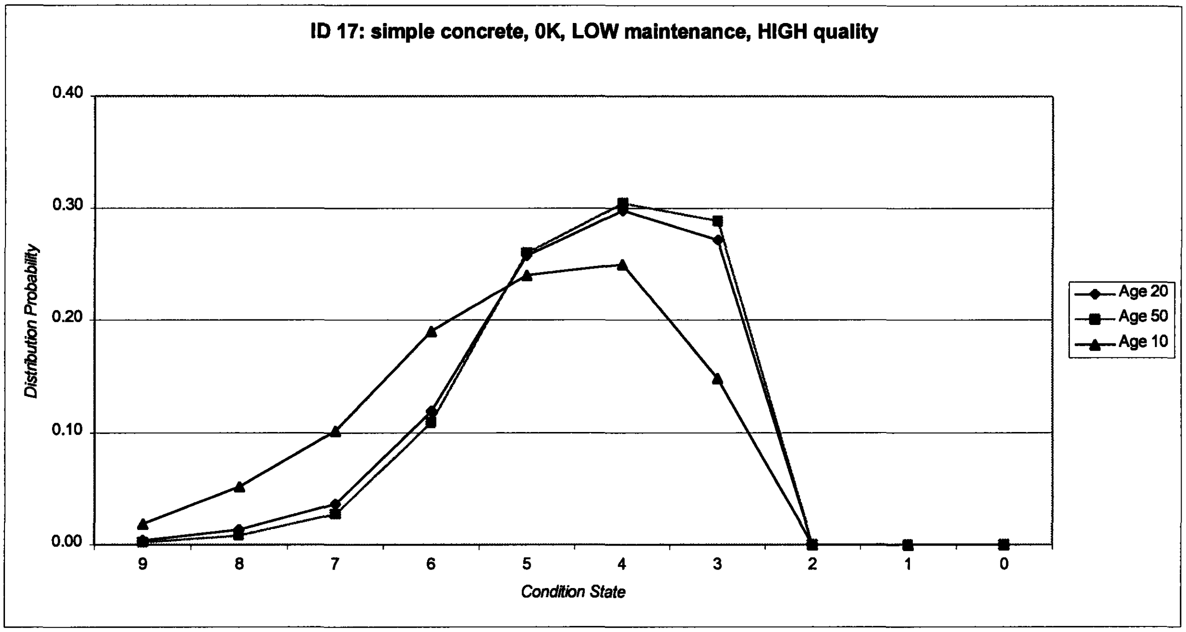


Chart 18: Scenario B (High Quality)

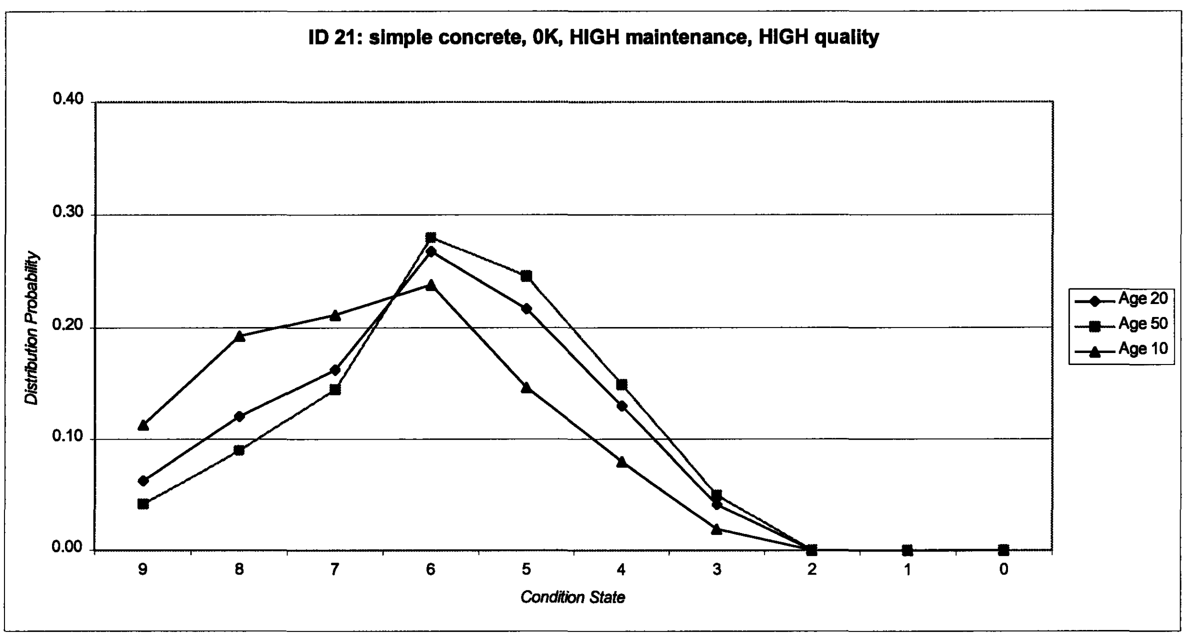


Chart 19: Scenario C (High Quality)

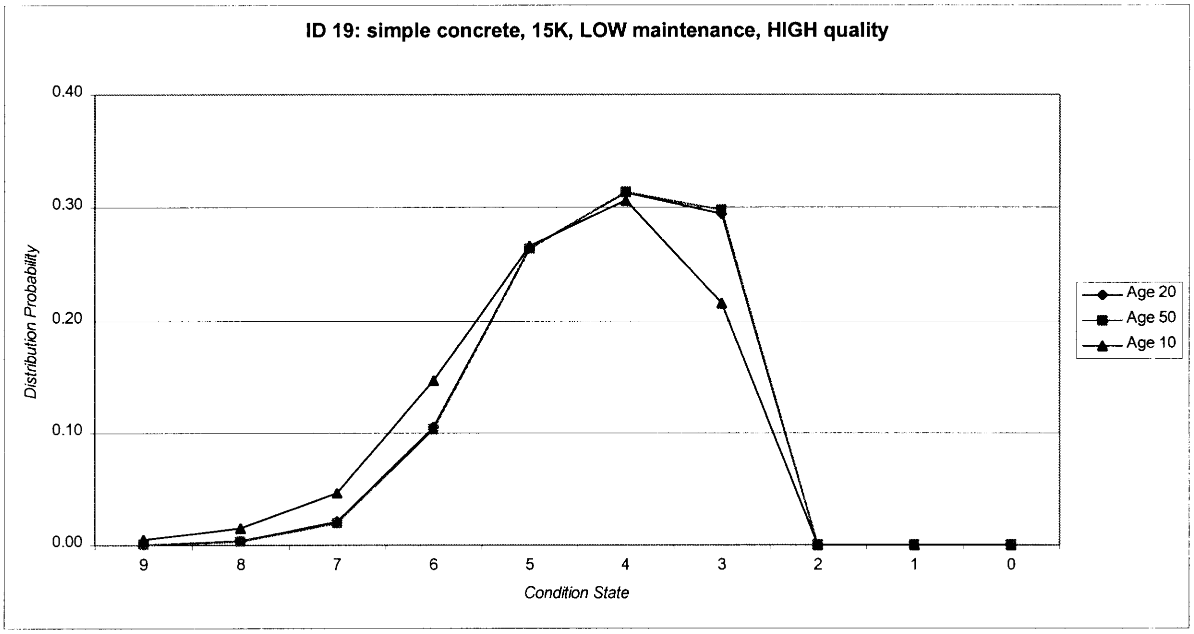


Chart 20: Scenario D (High Quality)

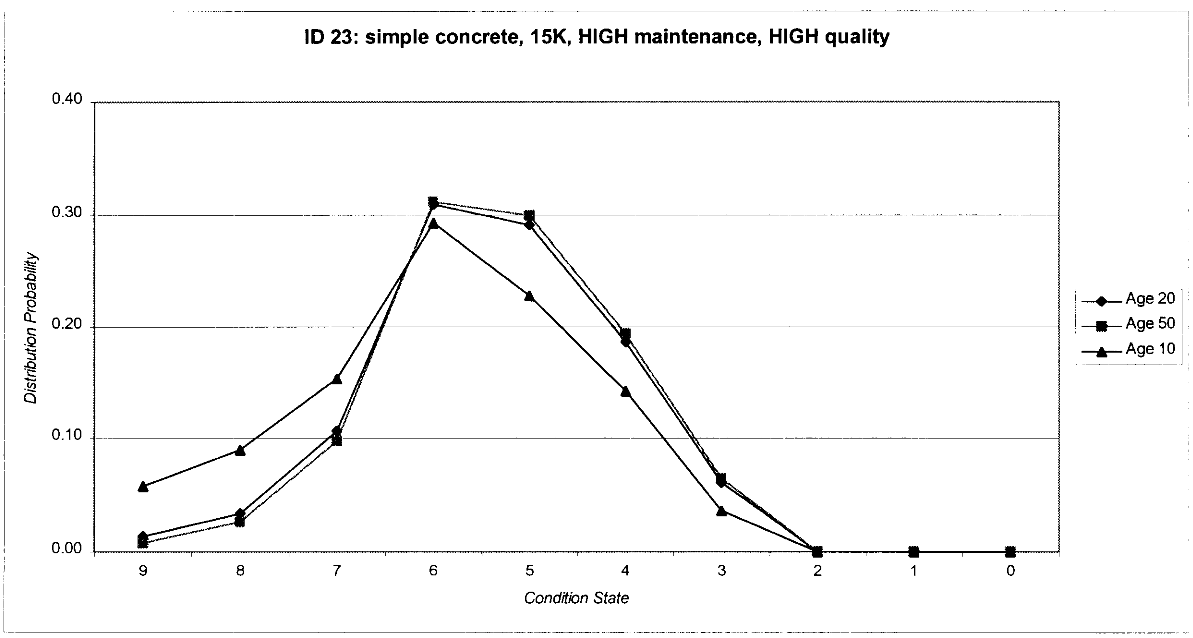


Chart 21: Scenario E (Low Quality)

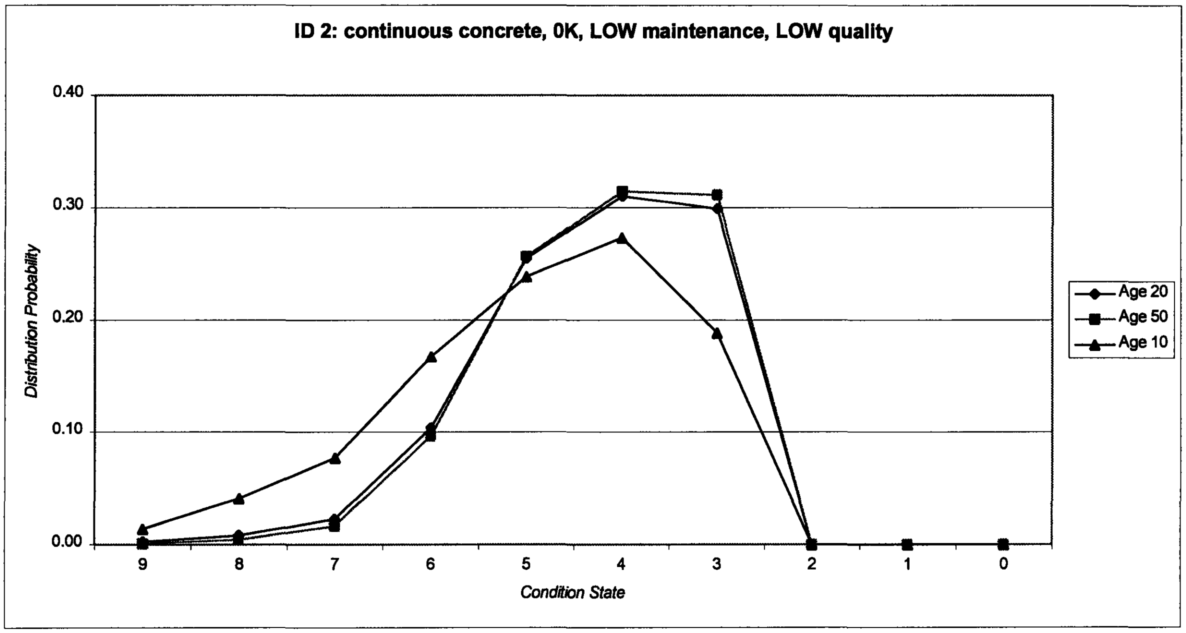


Chart 22: Scenario F (Low Quality)

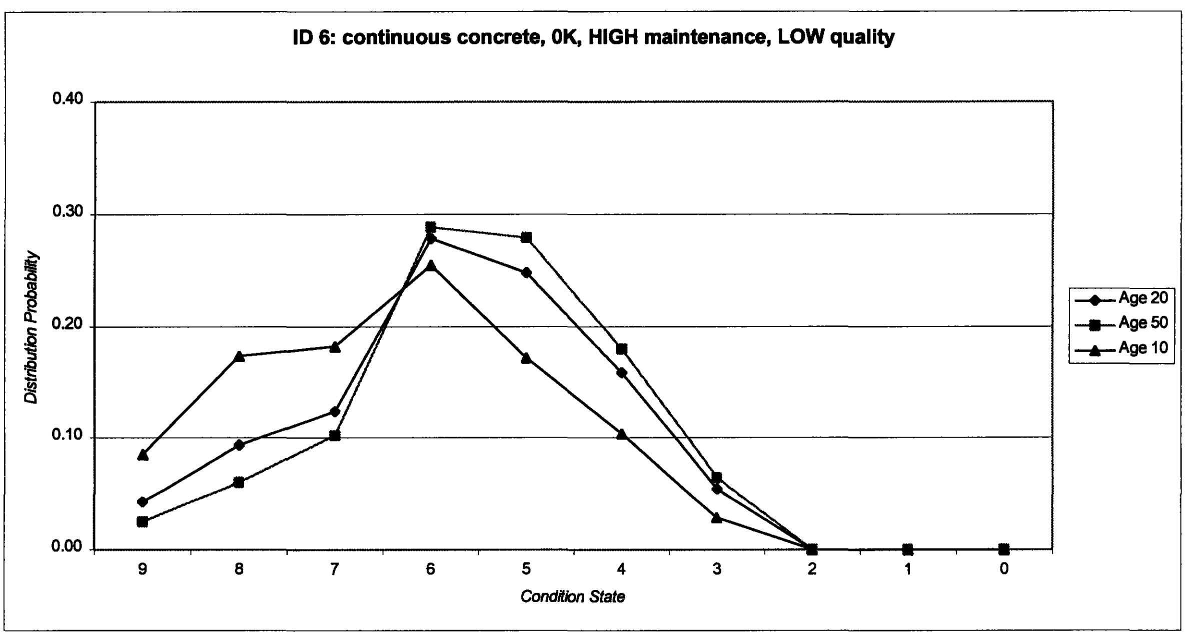


Chart 23: Scenario G (Low Quality)

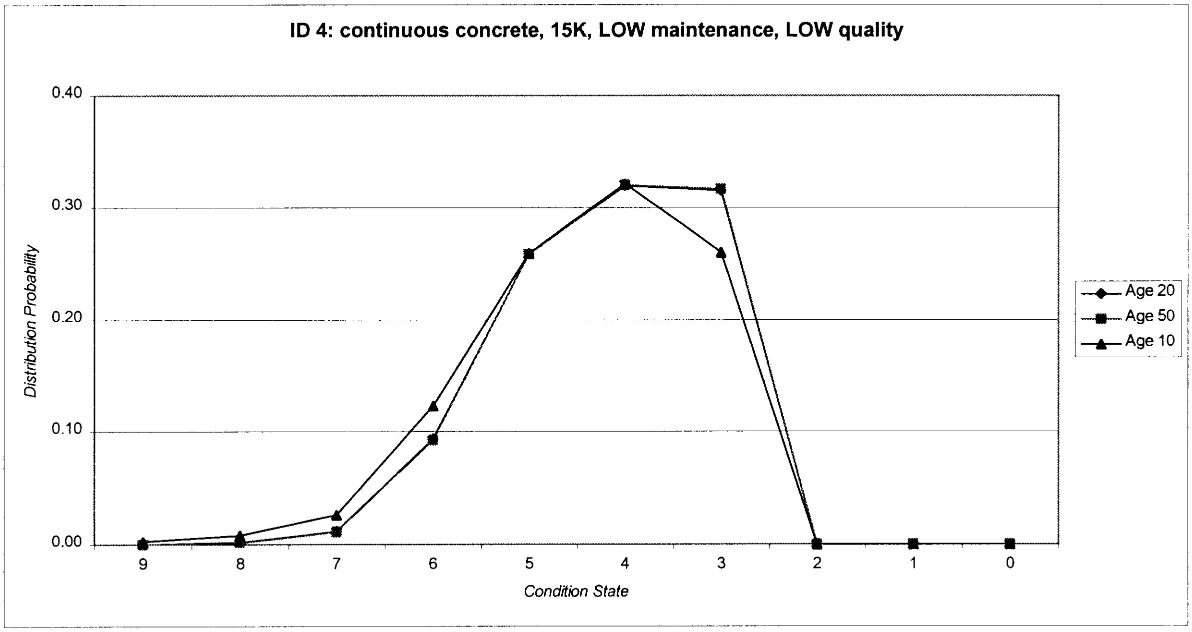


Chart 24: Scenario H (Low Quality)

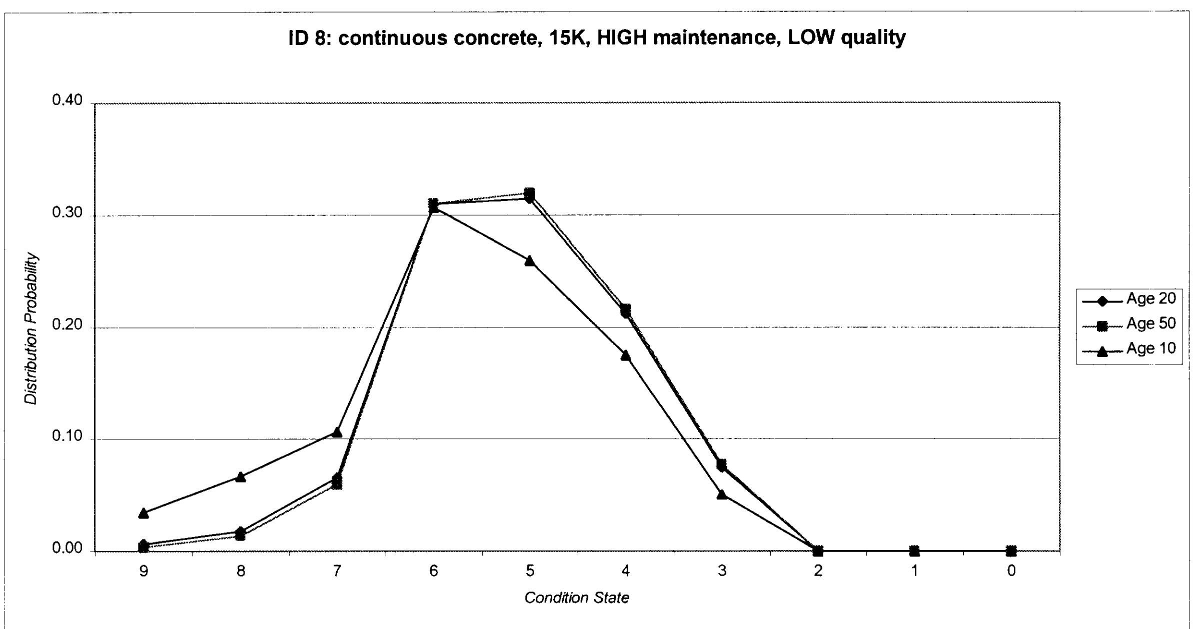


Chart 25: Scenario E (Med Quality)

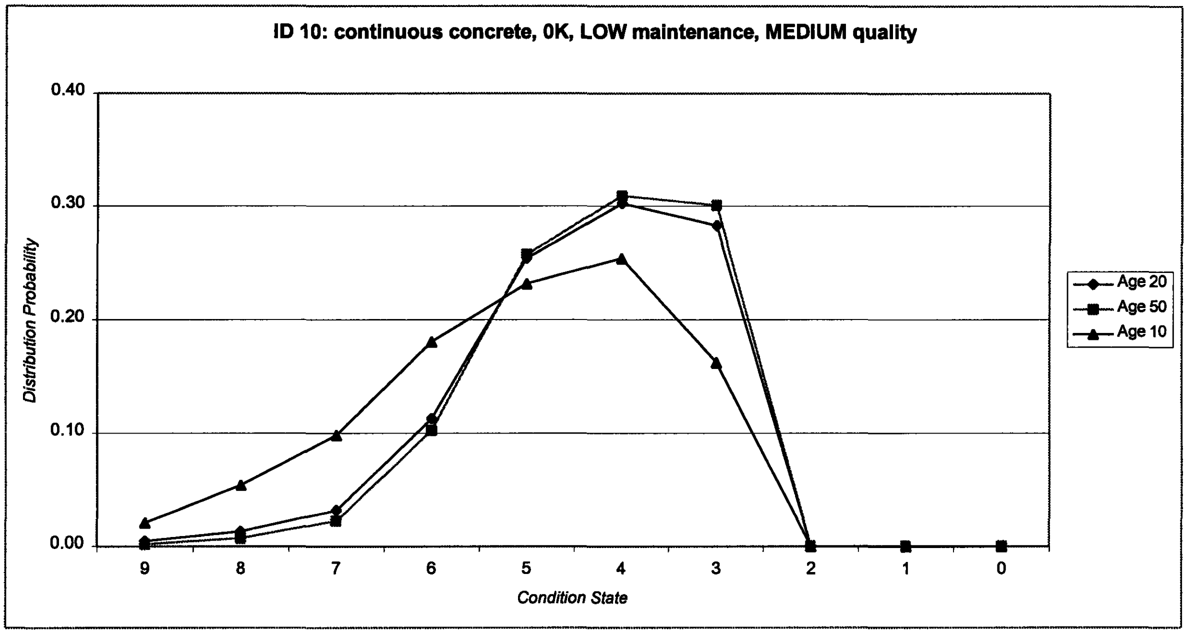


Chart 26: Scenario F (Med Quality)

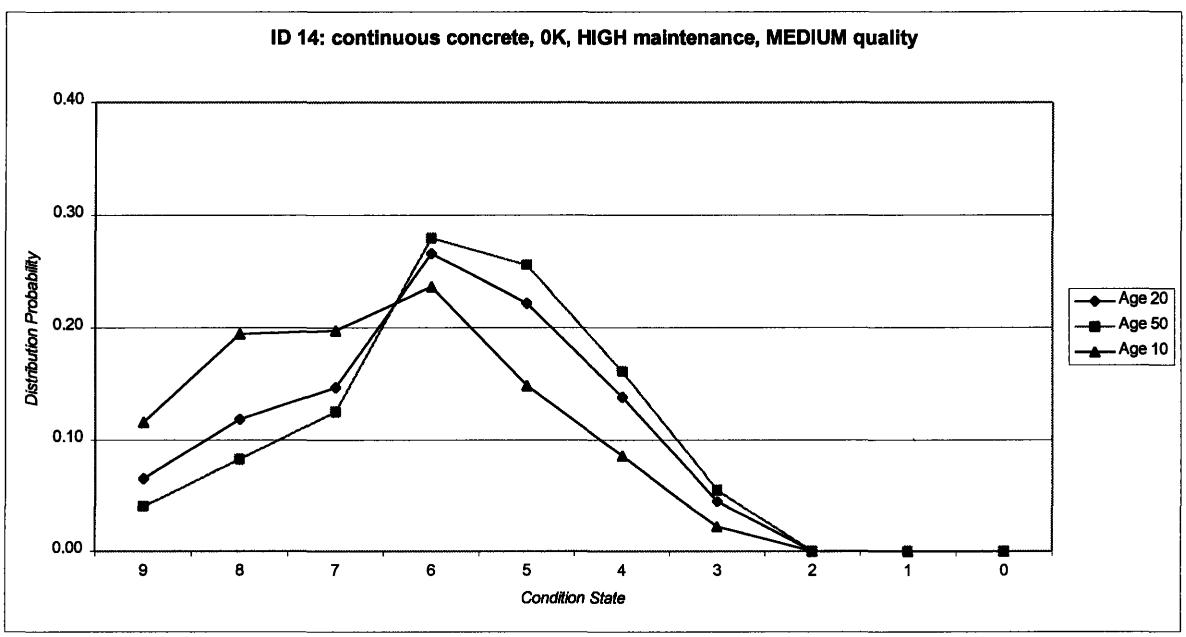


Chart 27: Scenario G (Med Quality)

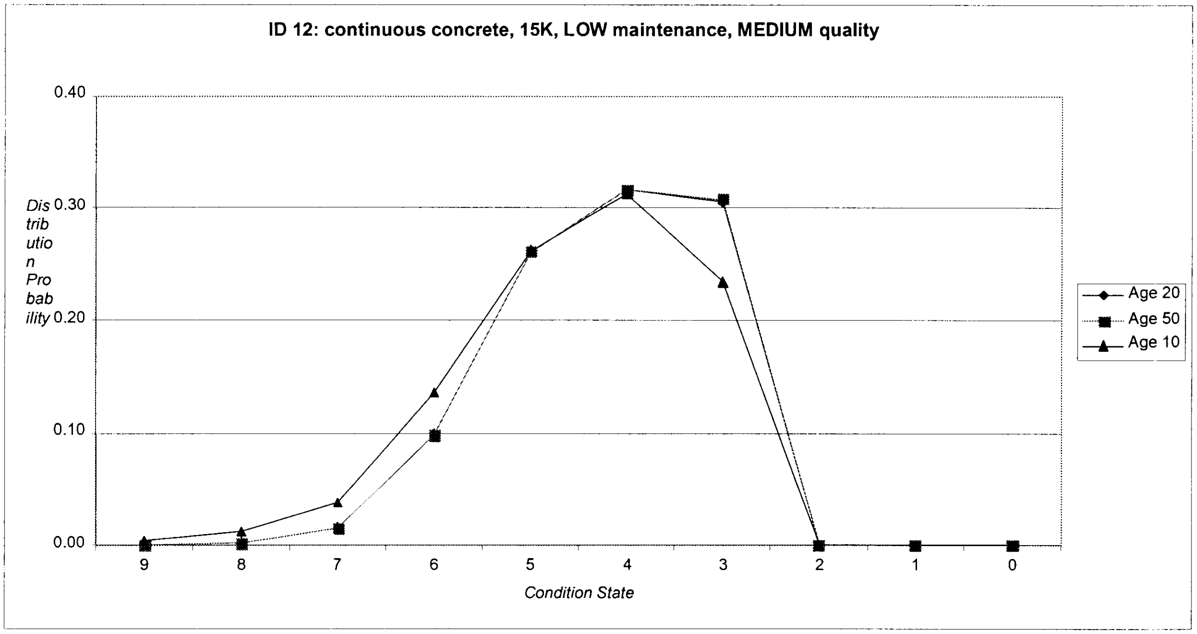


Chart 28: Scenario H (Med Quality)

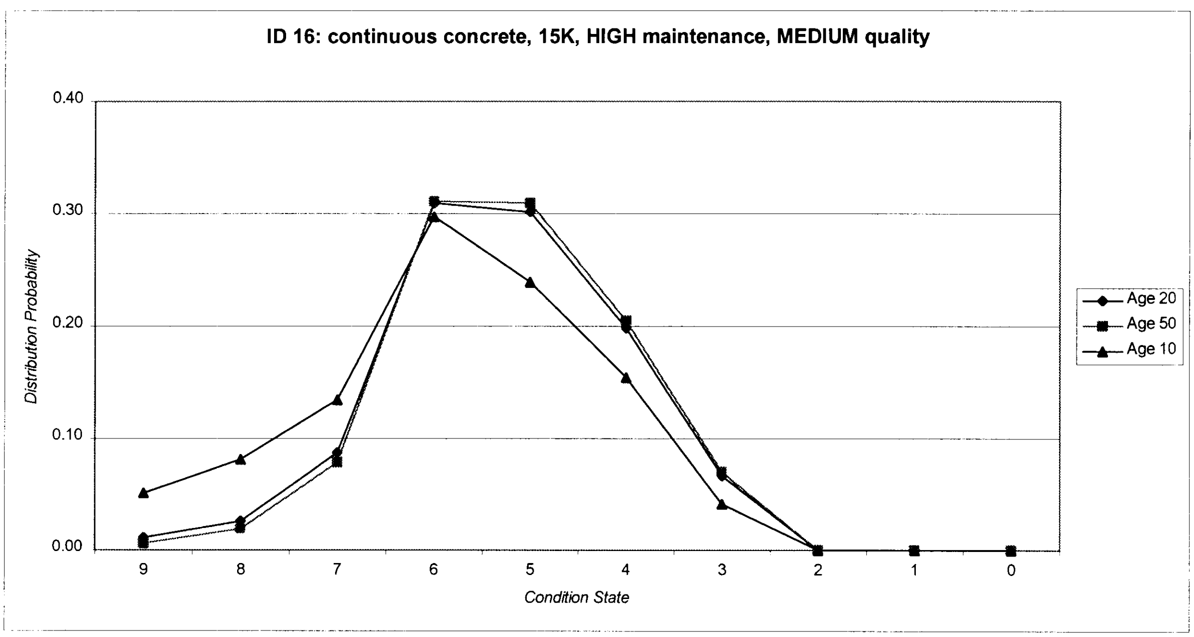


Chart 29: Scenario E (High Quality)

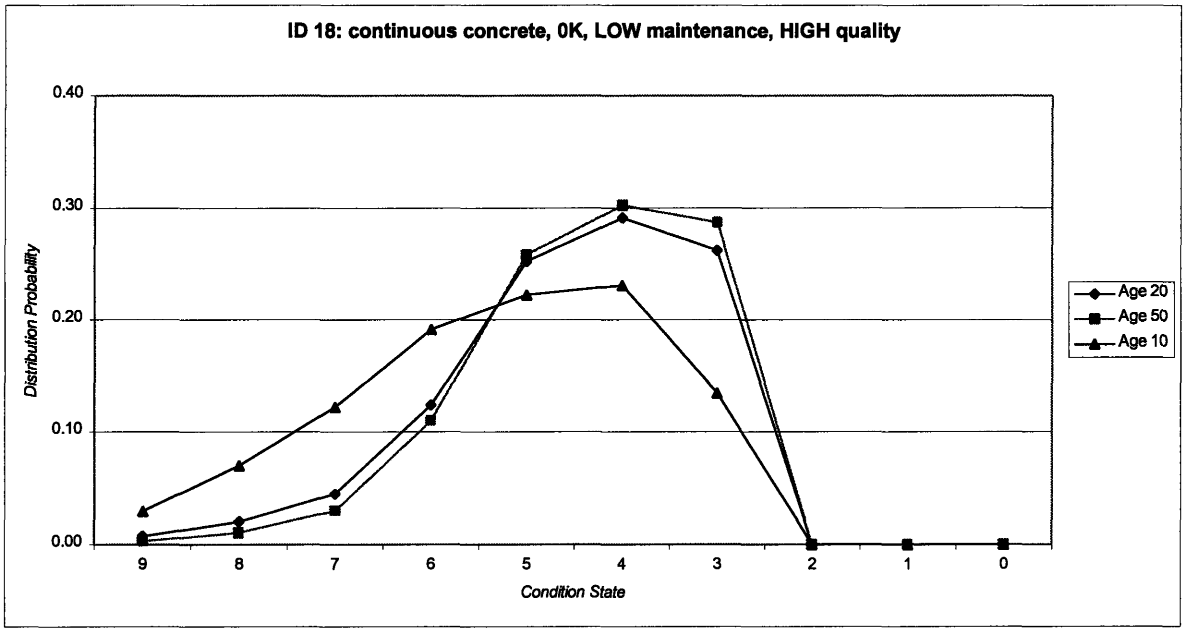


Chart 30: Scenario F (High Quality)

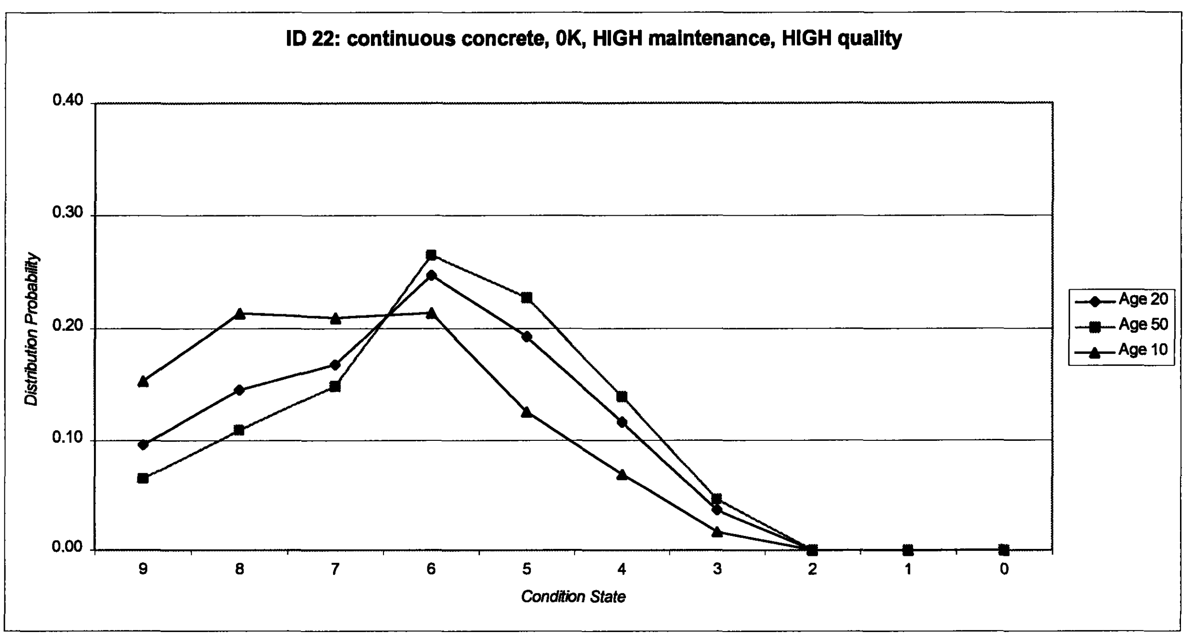


Chart 31: Scenario G (High Quality)

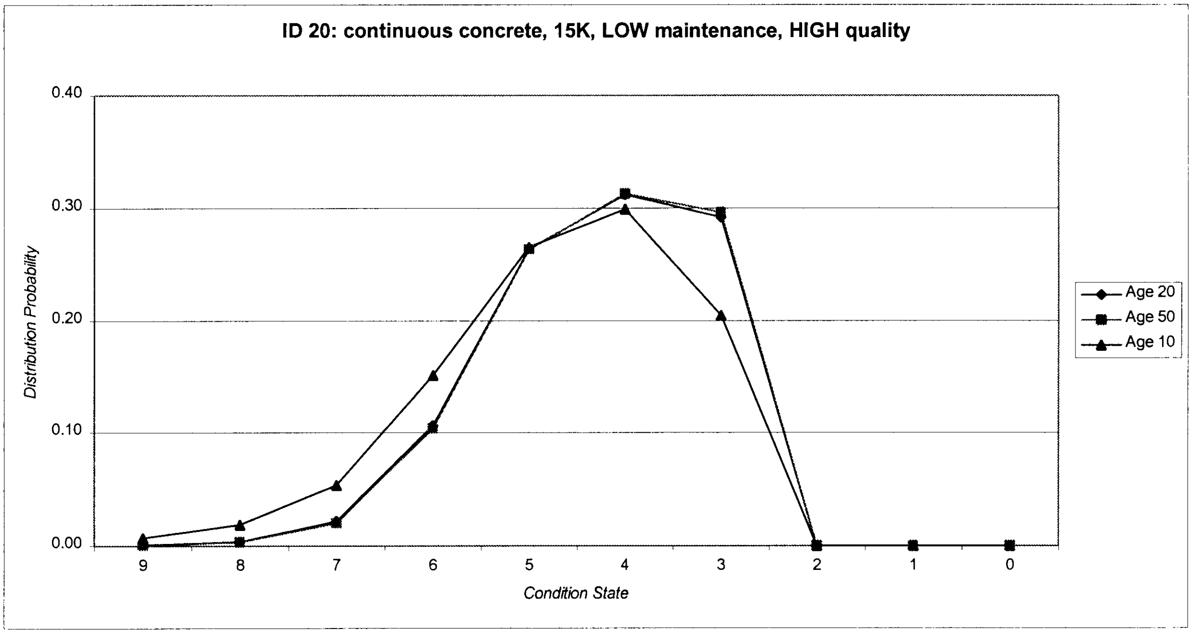
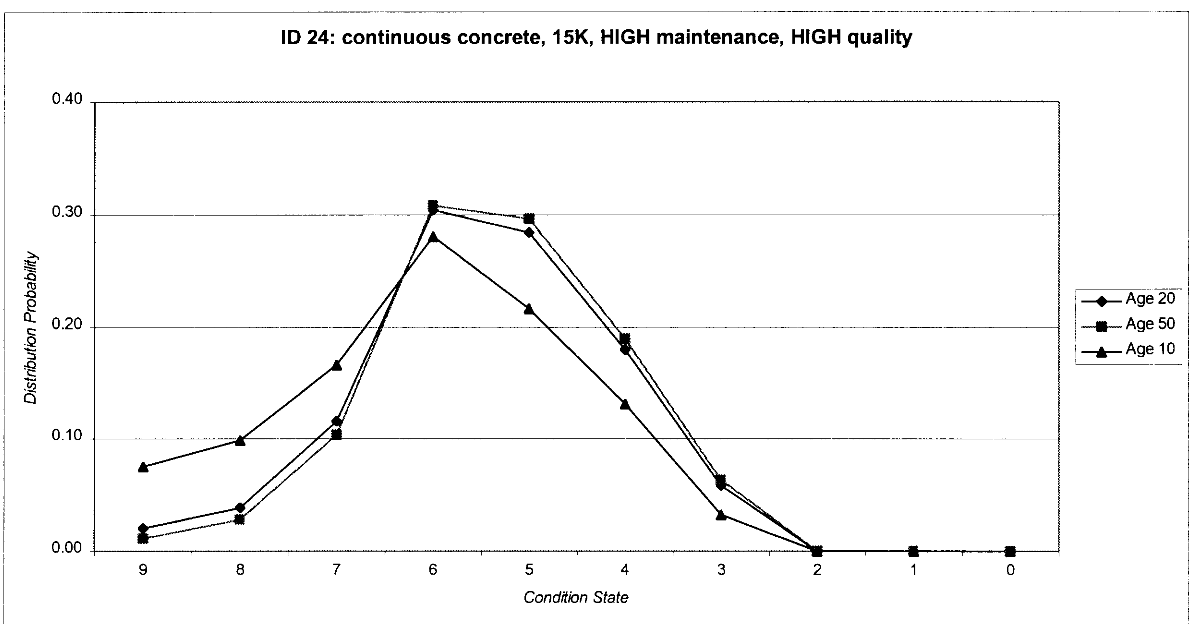


Chart 32: Scenario H (High Quality)



CHAPTER 5 APPLICATIONS

Now that we have discussed several approaches to the problem, and that we have interesting preliminary results, let us focus on some of the possible applications of the results. We will discuss the applications in general terms, and then relate them to the Tren Urbano context. Tren Urbano, introduced earlier on in sections 1.2 and 3.1.3, is the heavy rail system that is being built in San Juan, Puerto Rico. Scheduled to open in 2001, it is unique in its kind for it is the first Design-Build-Operate contract for an integrated Urban Rail project in the US (Salvucci, 1997). The state of progression and the contractual form of this rail transit project make Tren Urbano a candidate for the applications of the methodologies developed in this thesis.

Applications fall into two main categories. The first one, Cost Benefit Analysis, is dealing more with the economic aspect of the problem. The second, contract monitoring, is a continuation of the first, but emphasizes the physical condition of the infrastructure and its management.

5.1 COST BENEFIT ANALYSIS

Cost Benefit Analysis (CBA) is a very useful tool when it comes to making choices based on the economic and financial properties of the alternatives being considered. In the context of this thesis, CBA relies on Life Cycle Costing as a tool to make decisions between infrastructure systems and policies that have differing characteristics including initial conditions. Being able to predict the condition of an infrastructure under different initial provision standards (design and construction) is, therefore, a crucial input to such an analysis. The cash flows can be split into various categories as they relate to the condition of the facility. Maintenance related expenses depend in part on the current and expected future condition of the facility. User costs are directly related to the condition of the facility and they determine the level of service provided. Community disutilities linked to poor condition and rehabilitation works also impact the cash flow. Furthermore, operational expenses also depend on the condition because of the ripple effect that condition has on other activities. For example, rail track in poor condition can have a direct effect on the vehicle-operation expenditures. Finally, one could add the additional financing efforts (e.g. procurement, interest payments) that result from having to budget extra expenses not accounted for previously resulting, for example, from poor maintenance practices.

All these costs are directly or indirectly related to the condition of the infrastructure and its evolution over time. Therefore, there is a real value in understanding the variables that influence this condition and the nature in which they do so when planning for designing and assessing specific alternatives.

Cost Benefit Analysis, with the understanding of the sensitivities among decision variables and performance levels, allows to better choose among different alternatives. Not only can one assess the designs of these alternatives, but also the construction quality and maintenance policy. This allows for a comprehensive long-term view that ensures sound early decision-making based on economic considerations.

These applications are all very relevant to Tren Urbano because of the many design phases that remain to execute. Cost Benefit Analysis finds its application in the design of the future extensions of Tren Urbano. As of July 1997, the design of the first phase was almost complete. Nevertheless, an extension of that phase (phase I.A) and a new line (phase II) are already being considered. This provides enough opportunities to consider different design configurations and try to evaluate them thoroughly in order to pursue the most economically sound solution. In order to do so, a lot of data still needs to be collected. Assessing the costs of the construction, of operation, of maintenance and of the users is a requirement necessary to the implementation of a complete Cost Benefit Analysis estimation procedure. The operation of phase I is a very good opportunity to collect data to aid in the decisions made on phases IA and II. The value of such an approach to Tren Urbano is twofold. First, the authorities will be able to choose solutions that are most economical and meet current and future budget constraints. Second, public perception of the project can be enhanced through showing enough interest in User Cost. This allows for having a common ground in discussions with the communities.

5.2 CONTRACT DESIGN AND MONITORING

Another interesting application is the contract monitoring aspect that can be successfully implemented with the input from good condition assessment and prediction. This is particularly important in contexts where several actors with different goals are working on the same project. For example, consider a government aiming at serving its taxpayers by providing good performance while keeping expenditures within a certain budget limit, working together with a private contractor aiming at maximizing profits and a financing organization focusing on minimizing risk. Such a situation often makes it hard to strike an agreement among the different players, especially when conflicting interests are at hand.

This is where the methodologies developed in this thesis and the results they can provide are potentially useful. Because the methodologies allow for anticipating the many consequences of initial provision decisions in terms of level of service (performance) and operating costs, it gives all parties a decision ground and material to found contracts on and to monitor their performance. For example, a government agency can make sure that the contracted out maintenance activities are performed so as to guarantee the long-term goals of performance of the agency rather than solely the profit of the operator or contractor.

The Tren Urbano context also offers a unique opportunity in terms of contract design and monitoring. Since the Design, Construction, Operation, and Maintenance activities are contracted out to a private consortium, the government needs to be assured that its long-term goals are respected. With a contract period of 5 years of operation only, the consortium is not at risk for they will have to sustain only minimal deterioration that will hardly impair their ability to provide good service.

The option to renew the contract between the government agency and the consortium by another five years provides incentive for a longer-term view. Nevertheless, if initial provision conditions are compromised and if maintenance is not performed appropriately during this early period, serious negative effects on the long-term performance of the system may result. Thus, this calls for adequate contractual agreements where the government monitors the consortium so that they act in accordance with requirements dictated by long-term ownership.

The current (1997) contracts stipulate that all preventive maintenance activities need to be scheduled for each year, and the maintenance plan submitted to the government for approval (USDOT and the Government of Puerto Rico, 1995). However, there is no definition of what an acceptable maintenance plan is, and no indicators to monitor maintenance effectiveness and the condition of the infrastructure over time. Hence, the government needs to have the proper tools for overseeing the consortium's activities with regard to maintenance.

Developing the tools for clearly defining the responsibilities of each party would be a great benefit. Combining this opportunity to a monitoring process that would involve both parties and allow them to strike common decisions with the same tool would create a collaboration-oriented climate. If the contracts remain over short periods of time, close monitoring of the contractor will be necessary, in order to ensure that negligent profit making does not prime over the government's long-term objective. Furthermore, even if the contract duration is considerably extended so as to have the operator concerned about the long-term objectives as well, understanding how the system is sensitive to decision making is also important. Long-term contracts may provide an opportunity to make decisions together, because the objectives of each party involved are closer. To be able to make such decisions and fully understand their consequences, the approaches that we presented in his thesis provide a good foundation and starting point.

5.3 SUMMARY

Tren Urbano appears to be a perfect ground to implement the framework and concepts discussed in this thesis. Not only is deterioration going to be a crucial issue, because of the climatic conditions of Puerto Rico, but the contractual agreement that features a Design-Build-Operate scheme with short term responsibilities is also prone to generate initial provision and maintenance decision concerns if not addressed properly. Knowing the sensitivity of performance to the decisions that are taken can prove very valuable in ensuring that the governments meets its long-term objective, while still assuring a fair agreement with the consortium.

Hence, the methodology provides good opportunities to conduct comparative pricing studies and evaluate different design and policy configurations, through a Cost Benefit Analysis. Furthermore, it facilitates management by helping in the choices of policies and eases the collaboration of actors with different goals on the same project.

CHAPTER 6 CONCLUSION

6.1 CONCLUSIONS

In this thesis, we present a framework and address the problem of sensitivity of infrastructure performance to initial design and construction standards. The conceptual framework used throughout the thesis focuses on the potential importance of the decisions that need to be made up-front for capital- and maintenance-intensive infrastructure projects. This framework links the initial conditions of provision to the deterioration process; namely the effect of design and construction standards on maintenance requirements and deterioration rates. Maintenance also influences deterioration rates which contribute in determining the useful lifetime of the infrastructure. There are also cost and benefits components associated to the construction, maintenance and usage relative to the deterioration level. These cost figures generate the Life-Cycle cost associated with the facility. There are thus two dimensions to the problem of sensitivity of infrastructure performance to initial conditions. There is a cost dimensions that considers the problem from its most aggregate perspective, namely cost figures for both initial provision and performance. The deterioration process itself is the second dimension which focuses on how the condition of the infrastructure in the long run is affected by initial design and construction standards an under certain operation condition.

Due to the limited scope of this thesis, the results presented are not final conclusions since our objectives are primarily demonstrative in nature. This thesis focuses on illustrating the values of different methodologies towards solving the problem of interest with some preliminary results, rather than on arriving at final and comprehensive set of conclusions.

6.1.1 COST BASED CASE STUDY

Based on the conceptual framework summarized above, we chose to explore two approaches at two levels of detail to address the problem. The first approach was cost-based and considered the problem from its most aggregate perspective, namely costs resulting from provision and costs resulting from deterioration. In this study cost data gathered from Light Rail systems of US cities (Los Angeles, Pittsburgh, Portland (OR), Sacramento, and San Jose are used to estimate a model that predicted maintenance expenditures as a function of different design and construction cost variables. The coefficients obtained determine the preliminary approximation of the sensitivity of light rail system maintenance expenditure to design, construction and usage variables. This approach relies on two major assumptions:

- Design and construction cost variables are good proxies for quality.
- Maintenance activities and consequently costs respond to the needs of the system, mirroring its condition.

These assumptions are necessary to achieve the objective of this approach, namely determining the sensitivity of performance to initial conditions using cost figures. However, due to the very aggregate nature of the cost data, these assumptions are not comprehensively defensible. Nevertheless, the preliminary findings that the cost-based approach yielded are the following:

- For At Grade construction, higher expenditure, thus higher quality, decreases the amount of maintenance required during the period of operation, thus pointing out that the system is performing better
- For Elevated construction, however, higher expenditure results in increased maintenance requirements due to this increased complexity. This is attributed to the expenditure of elevated facilities being more closely related to complexity of design rather than initial quality from a deterioration perspective

The serious limitations to this approach and its applications are the following:

- Sample size is too small with 5 observations.
- The operations period of observation for the five systems is too short ranging from 4 to 10 years.

- Cost is not always a good proxy for quality as indicated by the interpretation of the second result above.
- Maintenance expenditures do not always relate to the actual condition of the infrastructure because budget constraints may be limiting and maintenance standards and policies vary across systems.
- The construction cost figures might not be consistent in their definition across the five system

This analysis yielded encouraging results, indicating a relationship between initial quality of provision and infrastructure performance. However, the numerous limitations of this approach motivate a less aggregate approach focusing more on the deterioration itself.

6.1.2 DETERIORATION BASED CASE STUDY

The objective of this case study is to demonstrate the validity and value of a less aggregate approach, based on the computation of the deterioration outcome as a function of various design, construction and operational variables. This approach allowed for computing bridge deck condition over time using a previously estimated deterioration model for bridge decks in Indiana. Since we could actually change the inputs (design and construction quality) for a series of scenarios that we specified, we had much more control on analyzing sensitivities to initial factors.

The preliminary results show the following:

- Bridge deck long-term condition is somewhat sensitive to Initial Quality of provision, especially under high maintenance standards.

- Bridge deck condition is impacted significantly by maintenance policies.

- Traffic and structural type play a lesser role in determining the deterioration rates of the facility.

- The better the condition of the facility, the more it is sensitive to these influential factors.

There are some limitations in the manner in which the deterioration-based case study was conducted. They include the following:

- High deterioration scenarios only are considered. This reduces the range of situations under which the results are valid. Of course, this limitation can be overcome by specifying a wider range of scenarios that represent situations less prone to deterioration.

- Maintenance effectiveness was assumed to be unaffected by age and condition state. To overcome this limitation, modeling the maintenance effectiveness as a function of age, condition state, and design and construction specifications is necessary.

- Some scenarios specified in the case study might actually not be common situations in the field. This can be overcome also through verification against a comprehensive bridge deck data set.

As is evident from the above presentation, these limitations are not inherent to the deterioration-based methodology. They are mostly limitations in scope that can be overcome via a more elaborate experimental setup. This was not pursued in this thesis since the scope of this study is not to arrive at final and comprehensive conclusions, but rather to demonstrate the applicability and value of the methodology.

6.1.3 APPLICATIONS

Exploring the two methodologies on determining the sensitivity of infrastructure performance to initial conditions, as was conducted through two case studies, is further motivated by the applications of the results. There are two major fields of application to the knowledge extracted from the methodologies and case studies, namely Cost Benefit Analysis and Contract Monitoring. Both are relevant to Tren Urbano, the Rapid Rail system that is being built in San Juan, Puerto Rico.

Cost Benefit Analysis allows for making choices between alternatives based on their physical characteristics, and economic and financial properties. Cost Benefit Analysis considers all the costs and benefits associated with the facility. Construction, maintenance and user cost are all directly or indirectly related to the condition of the facility and its evolution over time. Therefore, there is a real value in understanding the variables that influence this condition and the nature in which they do so when planning for designing and assessing different alternatives. The future extensions that are considered for Tren Urbano make this application very relevant in deciding upon the specifics of the extensions based on the assessment of costs and benefits of each alternative. The operation of the first phase is a very good opportunity to aid in the decisions made on subsequent phases.

Contract Monitoring is another application that can be derived from a good infrastructure condition assessment and prediction. This is particularly important when several actors with different goals are working together. Here also, Tren Urbano offers a good opportunity to apply the methodologies explored in this thesis. Tren Urbano is provided using a Design-Build-Operate provision format. In other words, the government agency in charge of Tren Urbano contracts out the design, construction and operation to a single consortium. The length of the contract is short, namely 5 years of operation. This would allow for disparities in objectives between the government, which aims at striking an optimal performance-cost trade-off, and the consortium which could aim only at maximizing profit. The option of extending the contract by another five years also allows for a longer-term view. The methodologies developed in this thesis potentially offer a common ground for discussion between both parties, so that they can reach a fair agreement. It serves to ensure that the government's objective of long-term performance is respected, as well as the consortium's profit within a fair margin.

6.1.4 FINAL REMARKS

The results of the case studies are only to be viewed as preliminary, and not as arriving at final and comprehensive conclusions. Nevertheless, they demonstrate the validity and limitations of taking an aggregate cost-based approach, or a detail-oriented deterioration-based approach. In the light of their possible applications, namely Cost Benefit Analysis and Contract Monitoring, these two approaches prompt for further research to overcome their data- or experiment-related limitations.

6.2 FUTURE WORK

The results presented in this thesis do not constitute a readily implementable solution to all the problem issues cited. Much rather, it lays the ground for further work that would achieve this objective. To reach this goal, there are immediate- and long-term research activities that are worth pursuing. In this section, we present these activities and discuss how they indeed overcome some of the actual limitations.

6.2.1 IMMEDIATE-TERM RESEARCH ACTIVITIES

Most of the further research in the immediate-term consists of addressing the limitations that we raised for both the cost- and deterioration-based approaches.

For the cost-based approach the following need to be explored:

- A more comprehensive data set which should present a larger sample size to overcome the statistical difficulties encountered in the modeling phase. A longer period of time for the facilities observed is necessary to allow for a more significant effect of deterioration on the facility to be observed.

- In terms of modeling, alternative specifications relations could also be investigated to test different types of relationships between maintenance expenditures and initial provision cost.

- The cost approximation for quality is hard to overcome. However, other data elements could be collected in order to render the approximations reasonable. For example, breaking maintenance expenditures down into reactive and preventive maintenance would already be a great improvement in the data set.

- Finally, it is not quite clear whether construction costs are always comparable across the systems being observed. For example, the Right of Way might already be prepared to receive a track or a highway in one case, while it would need to be cleared in another. Hence, a precise specification of what contributes to the construction costs is necessary to ensure that a set of systems are indeed comparable and can be used in the same data set.

Therefore, for the cost-based approach, most of the limitations can be overcome via a more comprehensive data set.

For the deterioration-based approach, the scope of the analysis could be extended to arrive at more accurate results as follows:

- Specifying a wider range of scenarios, excluding the less plausible ones via cross-checking with a data-set of actual bridge-decks. This would increase the accuracy of the sensitivity estimates, for it would avoid certain particularities such as the high deterioration situations of the deterioration-based case study.

- Using a model to compute the maintenance matrix, where maintenance policy could be condition dependent and maintenance effectiveness is a function of age, design and construction variables. This would allow for the introduction of further impacts of initial provision and temporal factors on the performance of

> the facility. This way, there would be two ways that the design and construction variables would influence the outcome, namely via the deterioration process, and via the maintenance effectiveness.

Furthermore, the relationship between initial quality and changes in outcome needs further investigation, based on the results obtained with the changes mentioned above. The patterns of sensitivities, as we pointed out in section 4.5.3, need confirmation. These patterns can also be refined to better determine the joint effects of variables.

Thus, there are several immediate-term improvements that could be introduced to the approaches that are undertaken. However, there are other considerations that would greatly enhance the results. The implementation of these improvements would require extensive additions to the current research, but could yield more definite answers to our questions. These longer term research activities are discussed next.

6.2.2 LONG-TERM RESEARCH

There are several long-term research activities that can be envisioned. First, with the appropriate cost models, the deterioration-based approach could be aggregated to the economic level. Then a Cost Benefit Analysis could be performed, using the computational results from this aggregation. Finally, the models could be integrated to allow for contract monitoring.

Aggregation of the deterioration based approach to the economic level

The deterioration-based model computes the condition outcome of the facility over time. With cost models it is possible to connect the design and construction activities to their respective cost, and the temporal maintenance activities to their respective cost, in accordance with the maintenance policy that has been adopted. In addition user costs as a function of condition can also be assessed. This way, the decision-maker can make better use of the results yielded by the deterioration model. A cost to every configuration of initial condition, usage and maintenance policy can now be available. This requires the following:

- Construction cost model to estimate the construction costs associated with the designs of the alternatives that will be analyzed.

- Maintenance cost model to estimate the cost related to each maintenance policy. This requires the breakdown of maintenance cost by the type of activity and its intensity. The type and intensity is in turn dependent on the condition state and maintenance policy.

- User cost model to measure the benefits and costs associated with the facility and its condition.

Cost Benefit Analysis

Once the condition outcome of the facility is associated with the corresponding cost figures, a Cost Benefit Analysis can be conducted by adding up the temporal cost and benefit figures discounted properly. Different scenarios can thus be compared via their Life-Cycle cost. This requires the following:

- Prediction of useful lifetime.

- Proper discount rate, corresponding to the type of infrastructure.

- The above mentioned cost figures.

Contract Monitoring

Finally, these cost figures can also serve to design and monitor contracts. Governmental agencies can now discuss design, construction and maintenance issues with their engineers, contractors and operators at both the physical and economic level. Therefore, exploring the various approaches for incorporating the physical and economic dimensions of the trade-off between initial conditions and long-term performance in the contracts design and monitoring process is critical.

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